LA-UR-21-26651

Approved for public release; distribution is unlimited.

Title:	Magnetic fields effects in ICF/HED systems well before Beta is anywhere near unity: experiments and recent theory
Author(s):	Flippo, Kirk Adler
Intended for:	LANL ICF Update and PR
Issued:	2021-07-13

Magnetic fields effects in ICF/HED systems well before *Beta* is anywhere near unity: experiments and recent theory

Kirk Flippo, Applied and Fundamental Physics, P-2

ICF Update, 2021

The HEDB Team (over the past 4 years)

Experiments

- Dan Barnak (P-24, U. Rochester))
- Alex Rasmus (P-24, P-2)
- Codie Fiedler Kawaguchi (P-24, P-2, UMich)
- Kwyntero Kelso (P-24, P-2, UMich)
- Noah Dunkley (P-24, P-2)

Collaborators

- Carolyn Kuranz (UMich)
- Eric Johnsen (UMich)
- Joseph Levesque (UMich, P-24, P-2)
- Petroz Tzeferacos (U. Rochester, Univ. Chicago)
- Edison Liang (Rice University)
- Amina Hussien (UC Irvine, U. Alberta)
- Alexis Canser (U. Bordeaux)
- Nomita Vazirani (Va Tech, P-24, XCP-6)
- Bhuvana Shrinivasan (Va Tech)

Simulation/ Theory

- Hui Li (T-2)
- Shengtai Li (T-5)
- Yingchao Lu (T-2, Rice)
- James Sadler (T-2)
- Andy Liao (T-2, Fuse Energy Technologies)
- Brian Albright (XTD-PRI)
- Jacopo Simoni (XCP-5)
- Jerome Daligault (XCP-5)

FLAG MHD Team

- Tom Gianakon (XTD-IDA)
- Chris Rousculp (XCP-6)
- Dennis Bowen (XCP-2)
- Nick Denissen (XCP-1)

This Team executed 7 shot days (Omega and EP) and 10,000’s of CPU hours over the past 4 years for 2 projects

- (LDRD DR) **High Energy Density B-fields (HEDB)**, to study the strength and effects of self generated B-fields in Shock-Shear like geometries
- (LDRD ER) **Turbulent Magnetic Dynamo (TMD)**, to study the generation, amplification (via Dynamo), and saturation of magnetic fields that pervade the universe

Publications from work in the talk

1. Lu et al. “MPRAD: A Monte Carlo and ray-tracing code for the proton radiography in high- energy-density plasma experiments”, **Rev. Sci. Instrum**. 90, 123503 (2019)
2. Mariscal, D., et al. First demonstration of ARC-accelerated proton beams at the National Ignition Facility, **Phys. Plasma**s 26, 043110 (2019)
3. Liao, A., et al. Design of a New Turbulent Dynamo Experiment on the Omega-EP, **Physics of Plasmas** 26, 032306 (2019)
4. Lu et al. “Modeling hydrodynamics, magnetic fields, and synthetic radiographs for high-energy- density plasma flows in shock-shear targets”, **Phys Plasmas**, 27, 012303 (2020)
5. Sadler, J. et al. “Kinetic simulations of fusion ignition with hot-spot ablator mix”, **Phys. Rev. E** 100, 033206 (2019)
6. Sadler, J., Li, H. “Magnetization around mix jets entering inertial confinement fusion fuel”, **Phys. Plasmas**, 27, 072707 (2020)
7. Sadler, J.D., Li, H., Flippo, K. A. “Magnetic field generation from composition gradients in inertial confinement fusion fuel”, **Philos. Trans. Roy. Soc., A**, (2020)
8. Sadler, J., Li, H. “Thermomagnetic instability of plasma composition gradients”, **Phys. Plasmas**, submitted (2020)
9. Sadler, J., Walsh, C., Li, H. “Symmetric set of transport coefficients for collisional magnetized plasma”, **PRL**, 126 (2021)
10. Fiedler Kawaguchi, C., et al “New Imaging Capabilities for HED Experiments”, submitted to **RSI** (2021)
11. Liao, A. et al. “Small-Scale Turbulent Dynamo in Laser-Driven Cone Experiments on Omega-EP”, **PRL**, in preparation (2021)
12. Flippo, K. A. et al. “First Observation of self-generated magnetic fields in HED experiments”, in prep for **PRL** (2021)
13. Li et al. “Can Self-generated Magnetic Fields change the Turbulent Kinetic Energy?” in preparation for **POP** (2021)
14. Dunkley, N, et al. “CR-39 pRad Analysis Using the Pepperpot Method”, in preparation for **RSI** (2021)

This work was motivated by some recent experiments showing B-field production via the Biermann Battery (BB) process

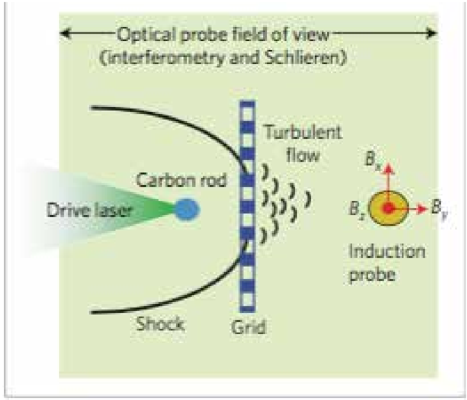
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times\left\{\mathbf{u}\times\mathbf{B} - \frac{\eta c^2}{4\pi}\nabla\times\mathbf{B} + \frac{c}{en_e}\nabla P_e\right\}$$

$$\frac{\partial \mathbf{B}_{\mathbf{bb}}}{\partial t} = -\frac{c}{e}\frac{\nabla n_e\times\nabla P_e}{n_e^2} \approx \boxed{-\frac{c}{e}\frac{\nabla n_e \times \nabla T_e}{n_e}}$$

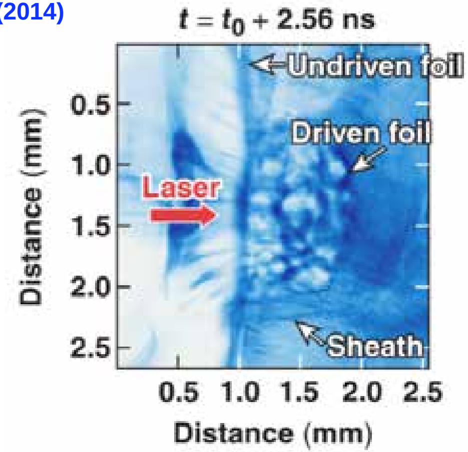
$$\boxed{\frac{\partial|\mathbf{B}_{\mathbf{bb}}|}{\partial t} \approx 0.5\left(\frac{\mathrm{MegaGauss}}{\mathrm{ns}}\right)\left(\frac{f}{0.1}\right)\left(\frac{T_e}{5\ \mathrm{keV}}\right)\left(\frac{100\mu\mathrm{m}}{\lambda_n}\right)\left(\frac{100\mu\mathrm{m}}{\lambda_T}\right)}$$

BB process has been confirmed in several HED experiments:

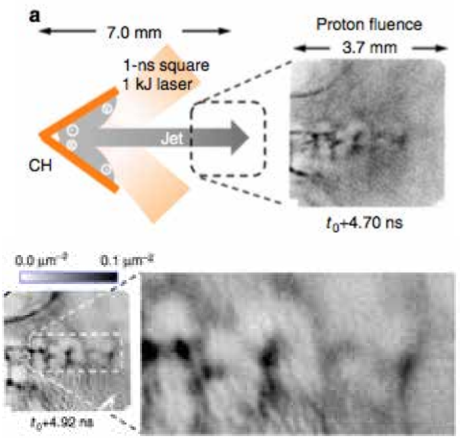
1) Turbulent B field experiment on Vulcan,
Meinecke et al. Nature Physics (2014)



2) RT experiment on Omega
Gao et al. PRL, 2013, 2015

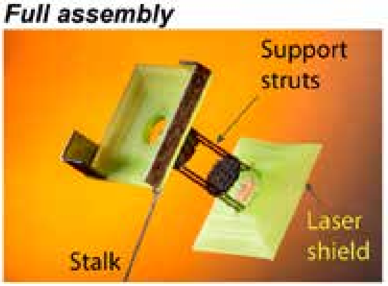


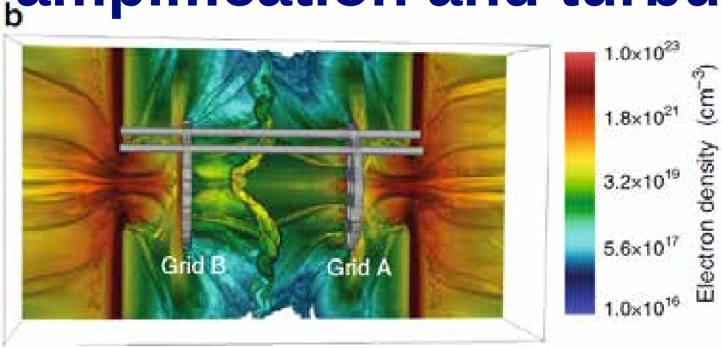
3) Jet experiment on OMEGA
Li et al. 2016, Nature Communications

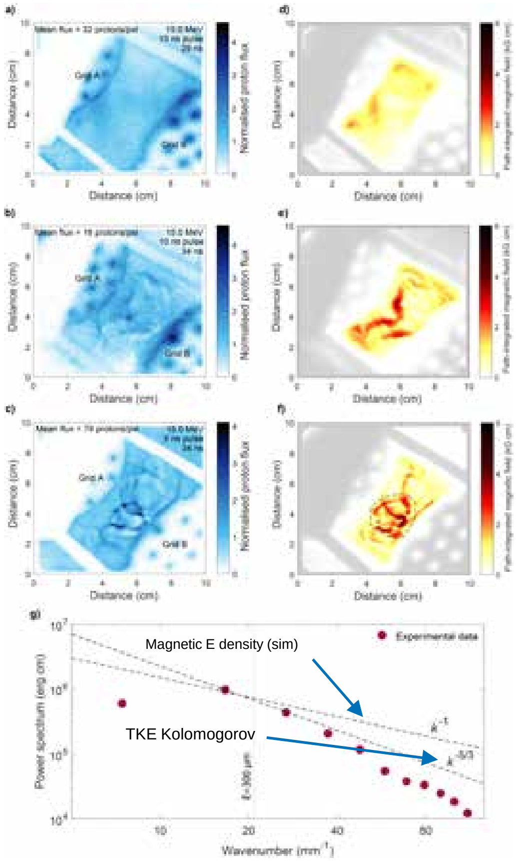


Still these are not dynamos, Rm is too low

And Recent Omega Experiments (and NIF) which showed more amplification and turbulent structure





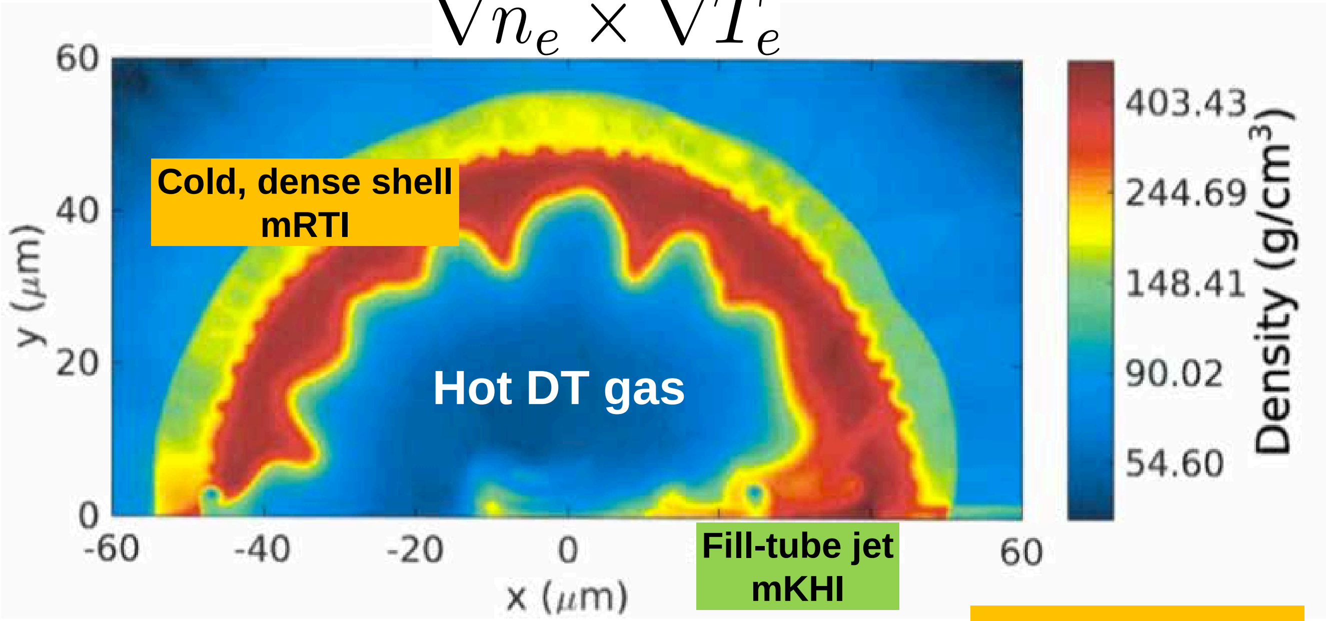


- Omega Experiment (Oxford collaboration) recently showed amplification with high Rm, but still not a dynamo.
- Vel 55 km/s, T_e ~ 450 eV, n_e~10^{20} /cm^3
- Re~600, Rm ~ 700, inferred 100 kG from an initial 4 kG (BB field).
- Is it saturated? It is cooling fast, and 5 ns drive work better than 10 ns drive. Thus likely not enough energy density in the system to make a dynamo (or keep it going)

This brings us to ICF, where we have interface instabilities, baroclinicity, vorticity generation, and many gradients

RTI, RMI, KHI: unstable, mixing, turbulence

$$\nabla n_e \times \nabla T_e$$

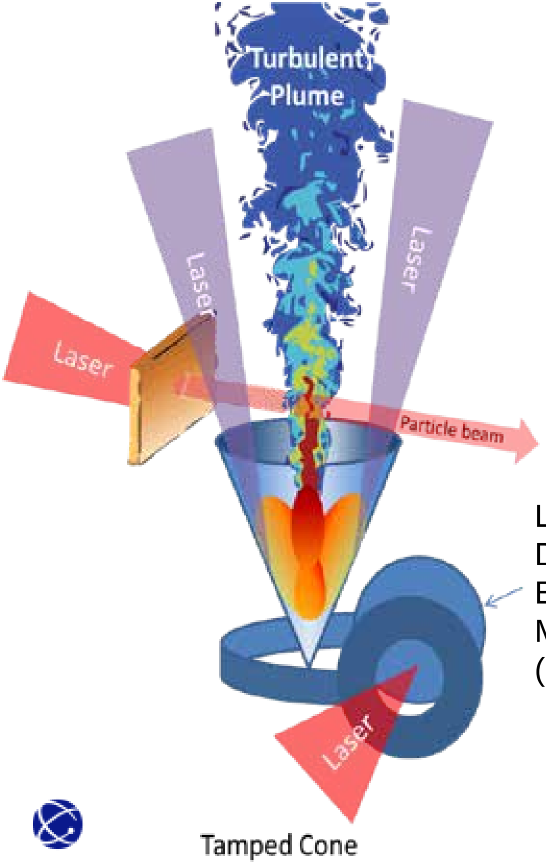


xRAGE simulation
Haines et al. 2020

Do B-fields matter?

Turbulent Magnetic Dynamo Experiments

We had an idea for a simpler platform for a Turbulent Magnetic Dynamo



Laser-Driven Electro-Magnet (LDEM)

Advantages Gained by Cone Design Over Foils:

1) Higher energy coupling
2) Higher temperature
3) Higher flow velocity
4) Higher density
5) Energy trapped longer
6) Tunable flows by adjusting laser and surface
7) Laser Driven ElectroMagnets (LDEMs) allow for tunable applied B-fields from 10 – 300 T to study saturation
8) Also allow for self-generated fields

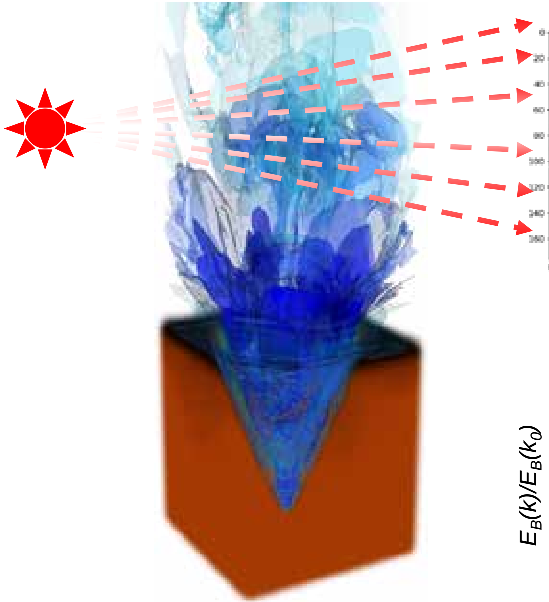
Flippo, Li, et al.

It looks like this in simulations

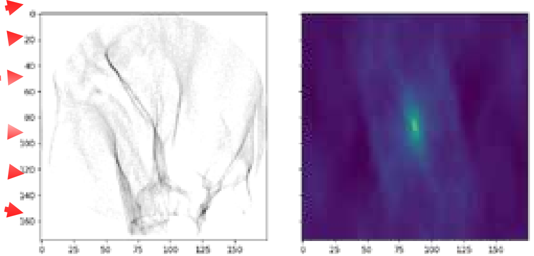
TMD Expt: (PI: K. Flippo, Co-PI: HL)

FLASH 3D magnetic field model

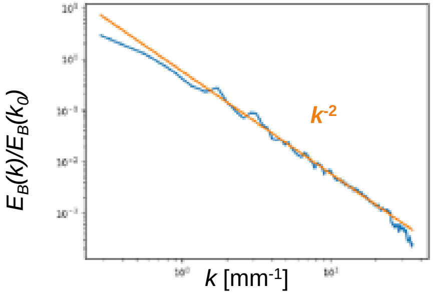
TNSA proton backlighter



30 MeV synthetic radiograph & autocorrelation



Power spectrum (FFT of autocorrelation)



1) Higher energy coupling
2) Higher temperature
3) Higher flow velocity
4) Higher density
5) Energy trapped longer

Flippo, HL, 2017
Liao et al. (2019)

We can diagnose this plasma with:
1. X-ray
2. Optical
3. P-Rad

Synthetic TNSA proton beam against simulated magnetic fields at 10 ns creates synthetic radiograph. Analysis[6] of the synthetic radiograph reveals the k^{-2} spectral energy distribution (SED) of magnetic energy. This SED arises in supersonic, compressively-driven turbulence.

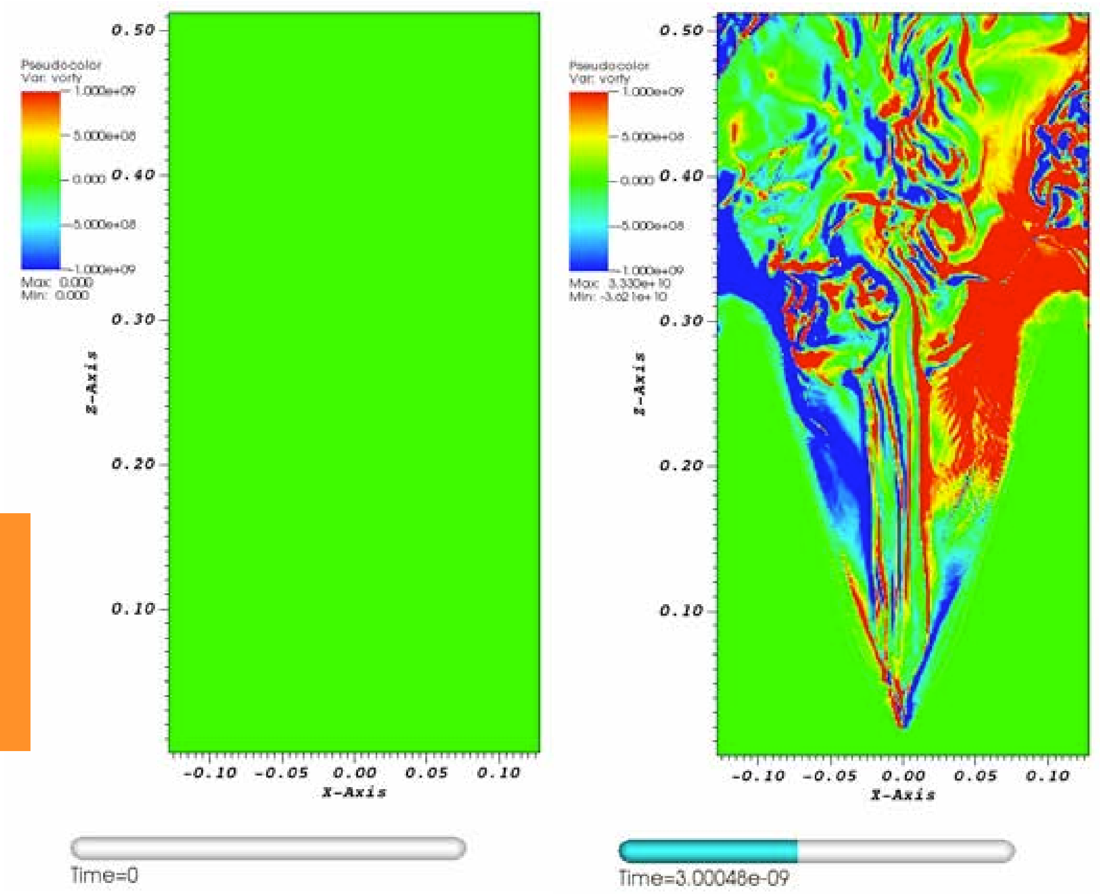
3D FLASH Simulation – Turbulence, Vorticity

Vorticity ~ 3e9

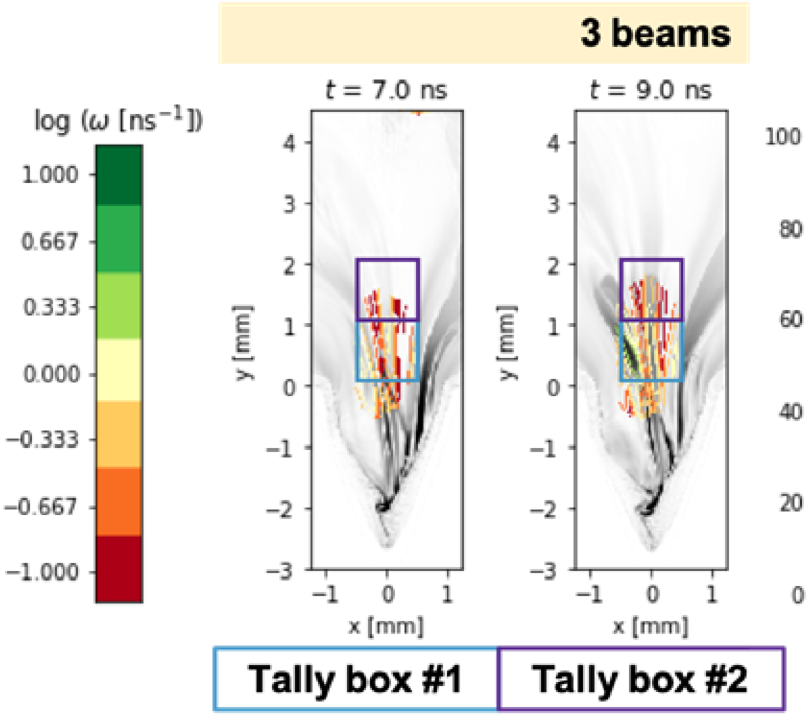
Duration ~ 3 ns

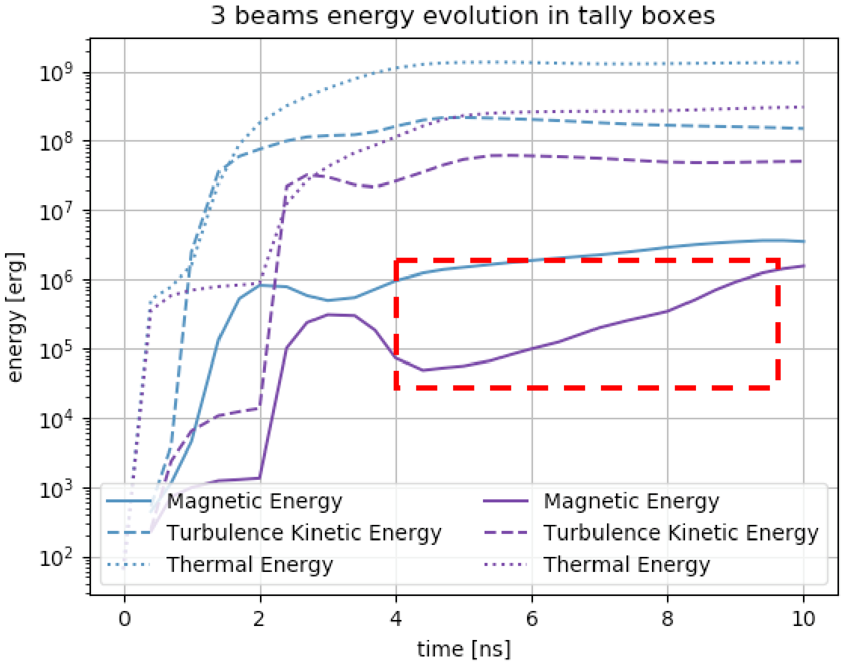
eddy turn-over:
3e9 * 3e-9
~ 10 turns
on ~ mm scale

There will be many more eddy turn-over times for smaller scales. This is very favorable for turbulence amplification of magnetic fields.



Exponential Growth of Magnetic Energy Reveals Turbulent Dynamo

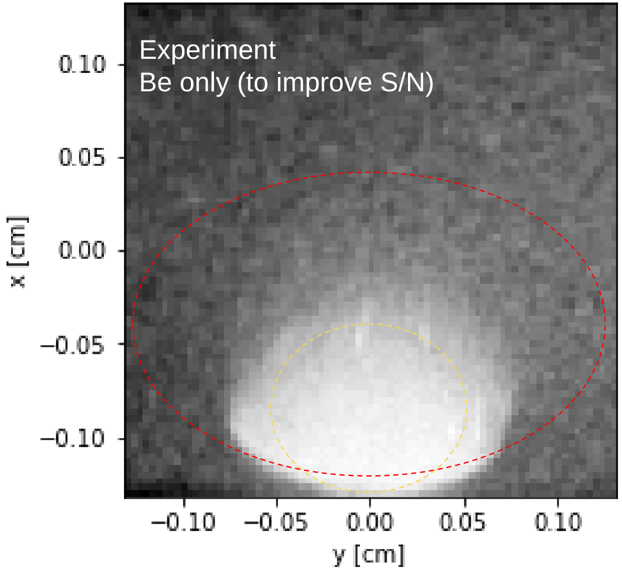


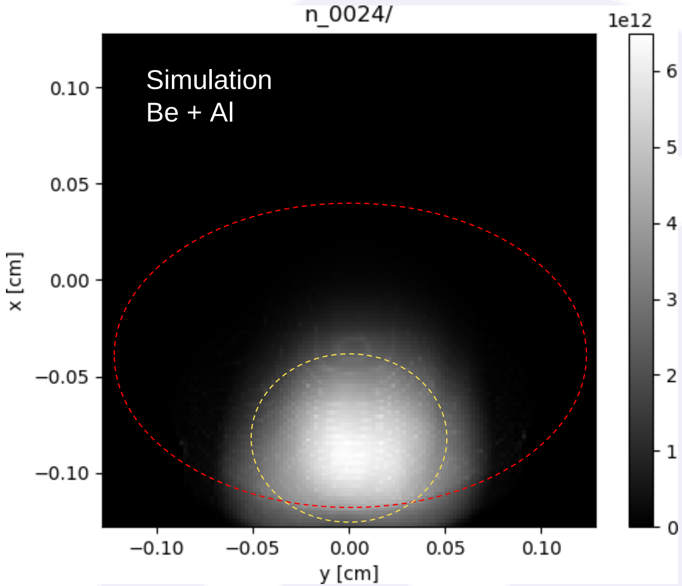


Strong exponential growth over many ns suggests observable turbulent dynamo

Liao et al. POP (2019)

Consistency between X-ray measurement and Sim. shows Te ~ 1.5 keV

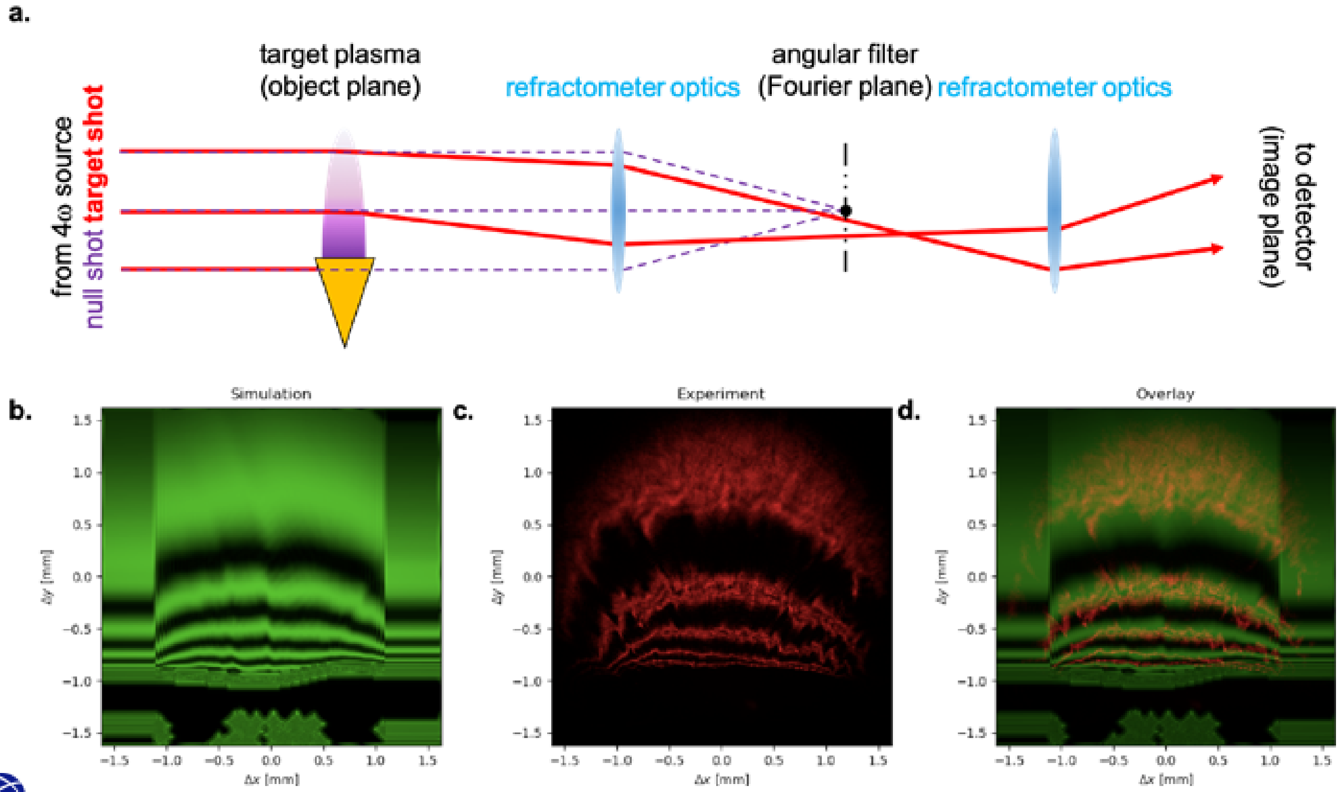




Emission region fills to and highlights proximal cone lip

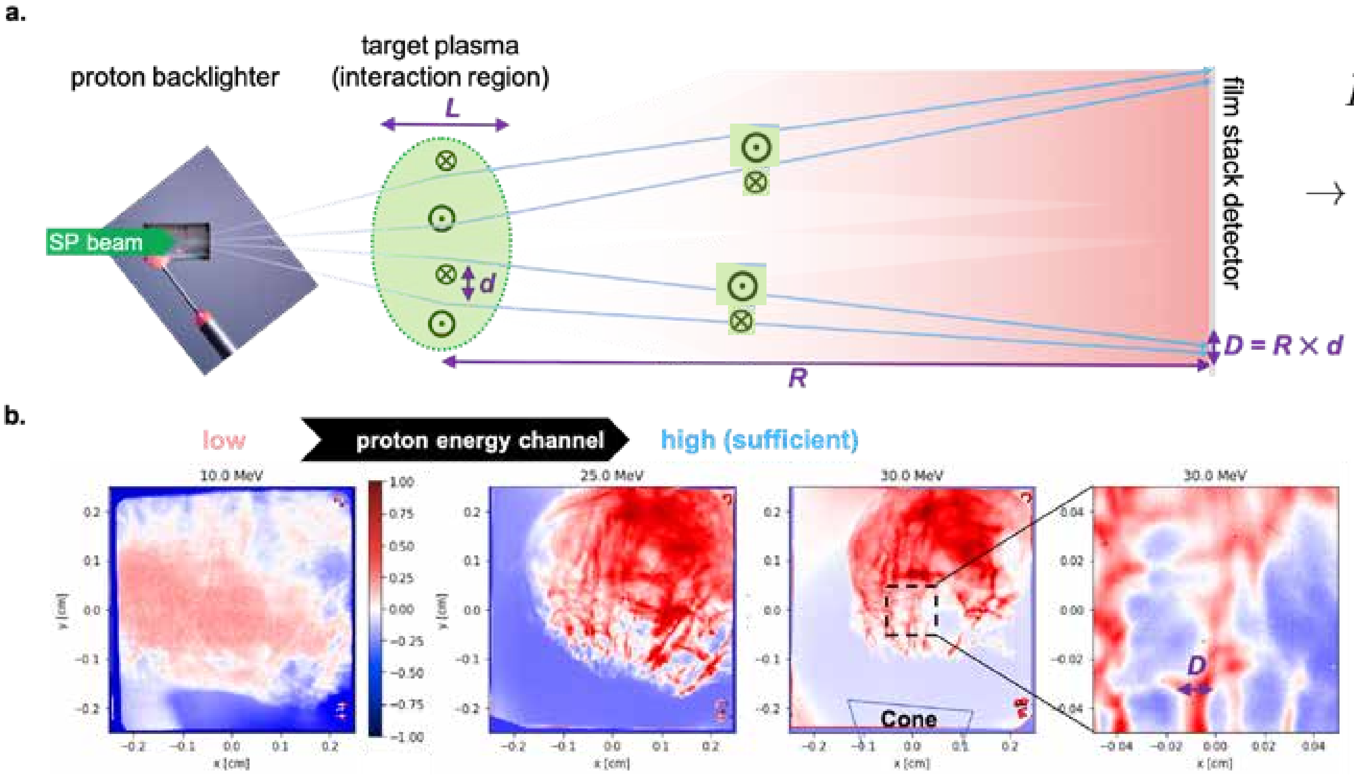
Liao et al. (2021)

Good Agreement between Simulation and Density Measurement: angular filter refractometry plasma density diagnostic



Plume density
n_e

TNSA P-rad Analysis: Shows B-field growth



$$B \sim m_p c v D / q R L$$

$$\rightarrow \int B \cdot \mathrm{d}L \sim 10^3 \ \mathrm{G{\cdot}cm}$$

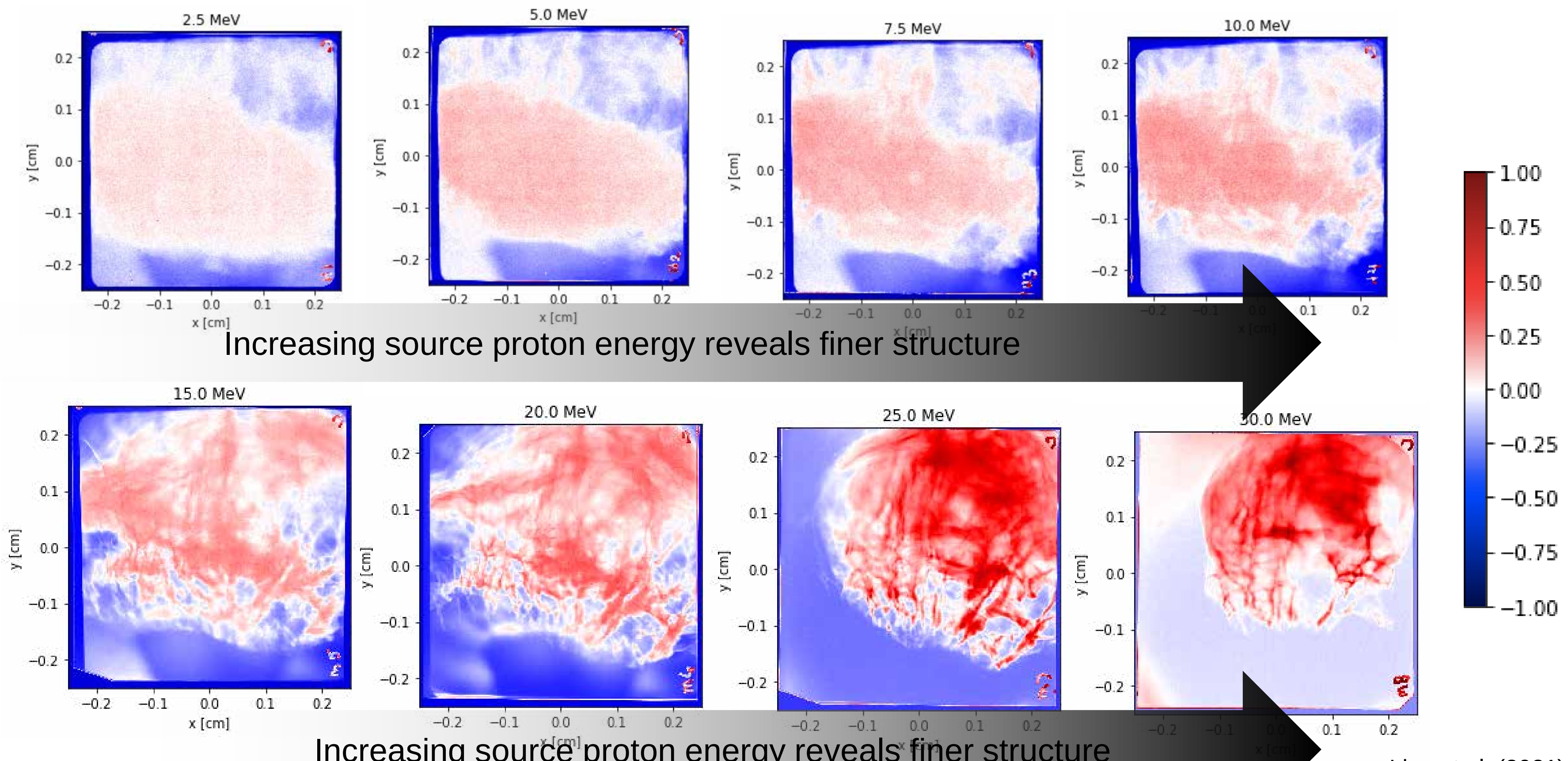
$$L \sim 100 \ \mu\mathrm{m}$$

➡ B 10^5 G

t = 8 ns

Liao et al. (2021)

Details in Flux Images are Revealed with Higher Source Proton Energies



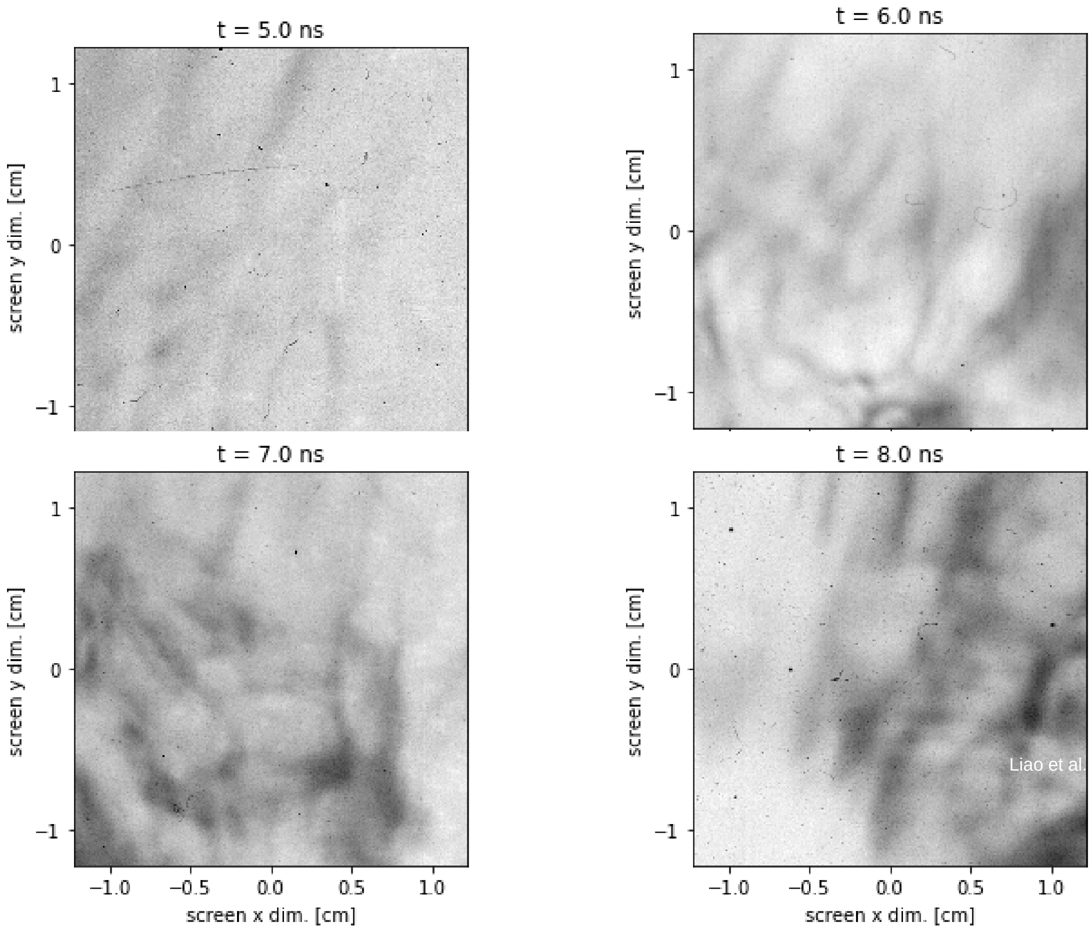
Increasing source proton energy reveals finer structure

Increasing source proton energy reveals finer structure

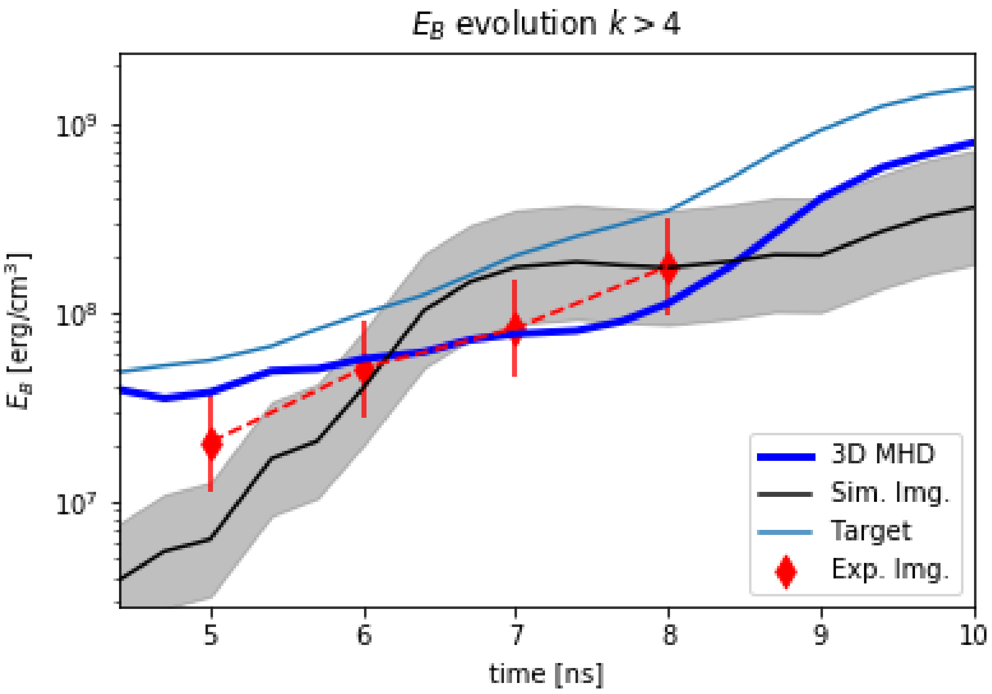
Liao et al. (2021)

Experimental pRad Images show growth in structure over time

TNSA P-rad Images at T = 5, 6, 7, 8 ns



Magnetic Energy Evolution Shows Growth of B-field Energy



$$n_e \sim 10^{20}\ \mathrm{cm}^{-3},\ T \gtrsim 1.5\ \mathrm{keV}$$

$$\mathrm{Re/L} \approx 6 \times 10^4\ \mathrm{cm}^{-1}$$

$$\mathrm{Rm/L} \approx 10^5\ \mathrm{cm}^{-1}$$

Take L ~ 0.3 mm

Then, we get:

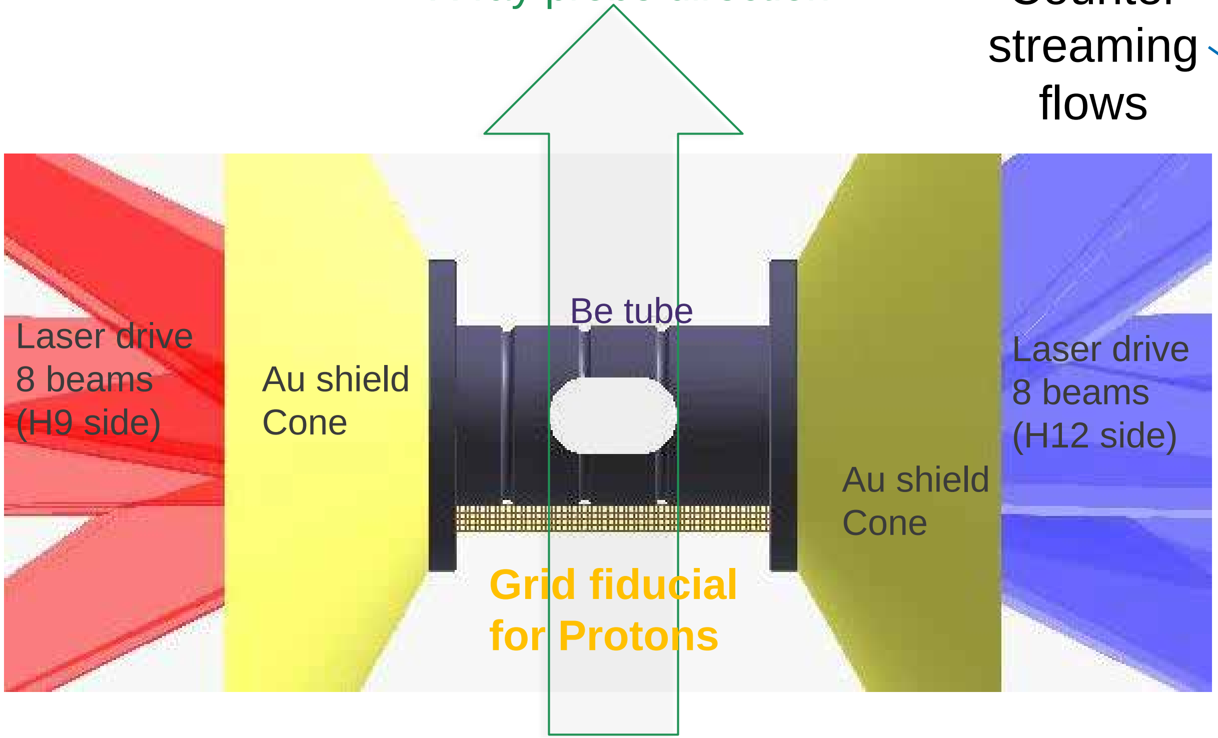
$$\mathrm{Re} \approx 1800,\ \mathrm{Rm} \approx 3000,\ \mathrm{and}\ \mathrm{Pm} \approx 1.67.$$

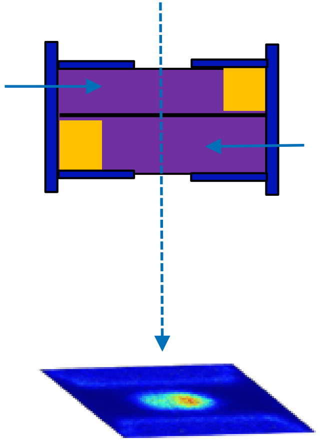
Turbulent dynamo is expected, consistent with our experimental measurements Liao et al. (2021)

HEDB Experiments

HEDB uses a new Experiment Designed to Use Our Shock-Tube Cylinder and Uses Shear Flows to Produce B-fields

- **Shear generates magnetic field in the center, which is probed by x-rays and protons**

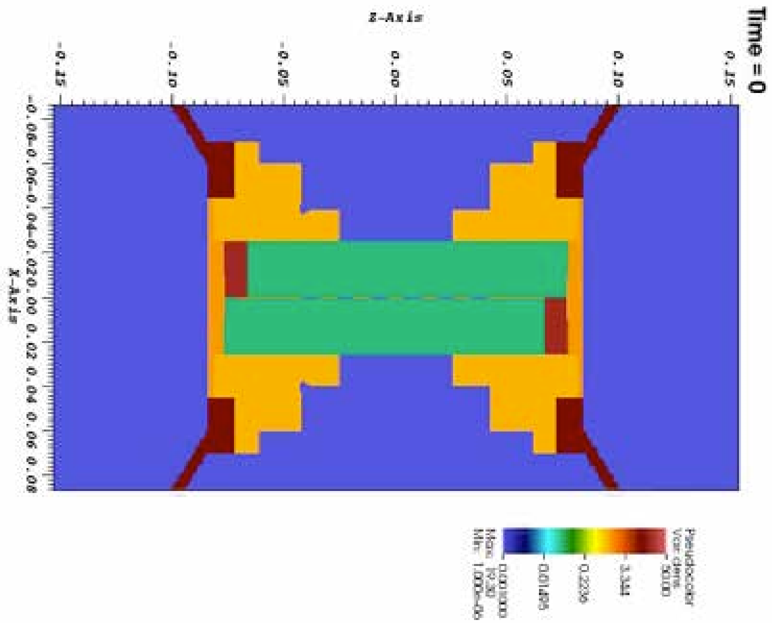




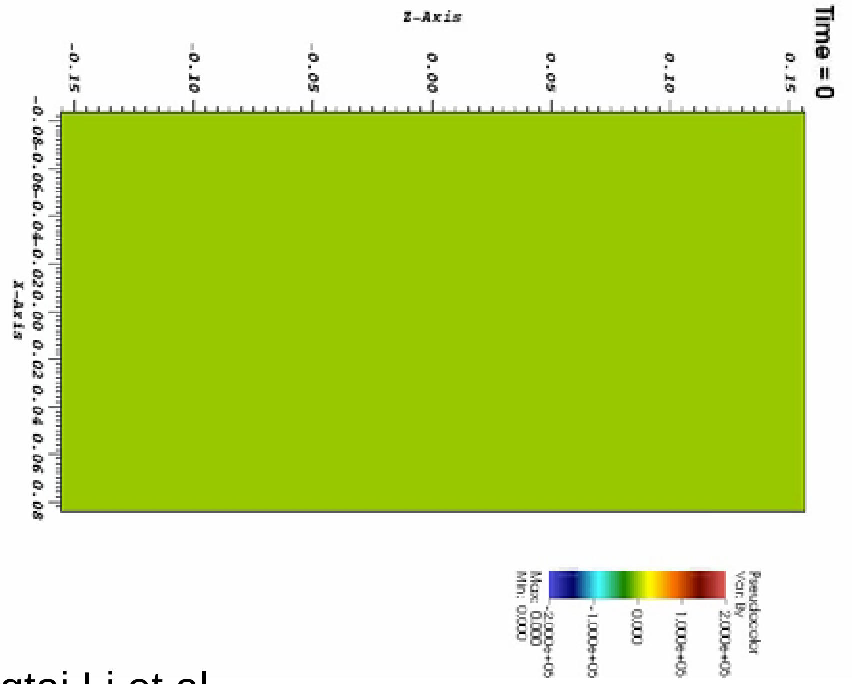
View along proton radiography axis

3D extended, radiation magnetohydrodynamic simulations (FLASH) and prad analysis tools (MPRAD)

density

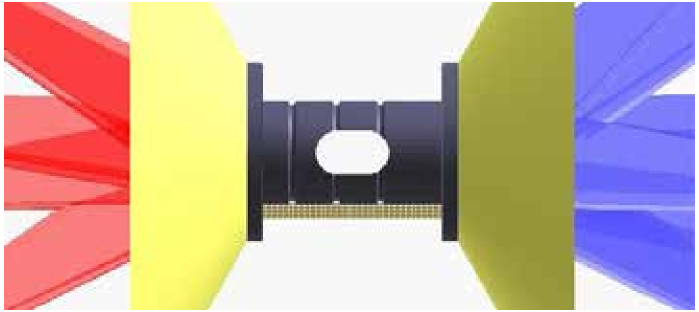


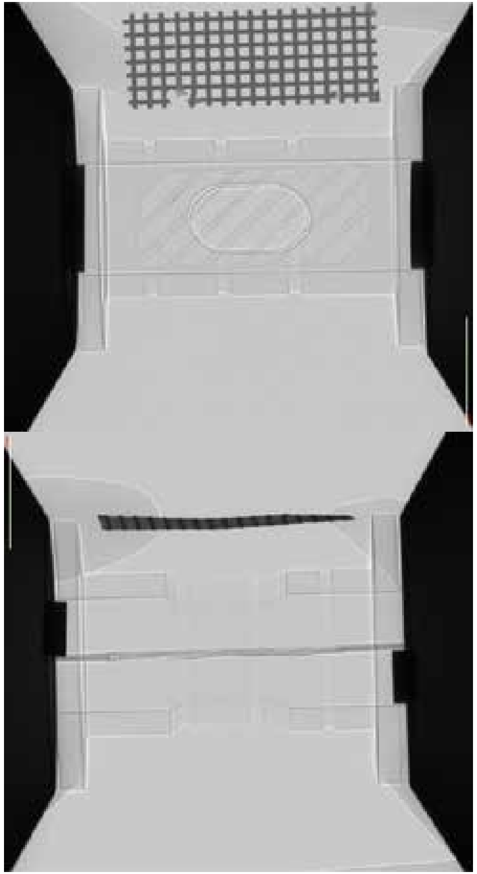
Magnetic fields



Work led by Shengtai Li et al.

Static X-ray radiographs of targets showing foil





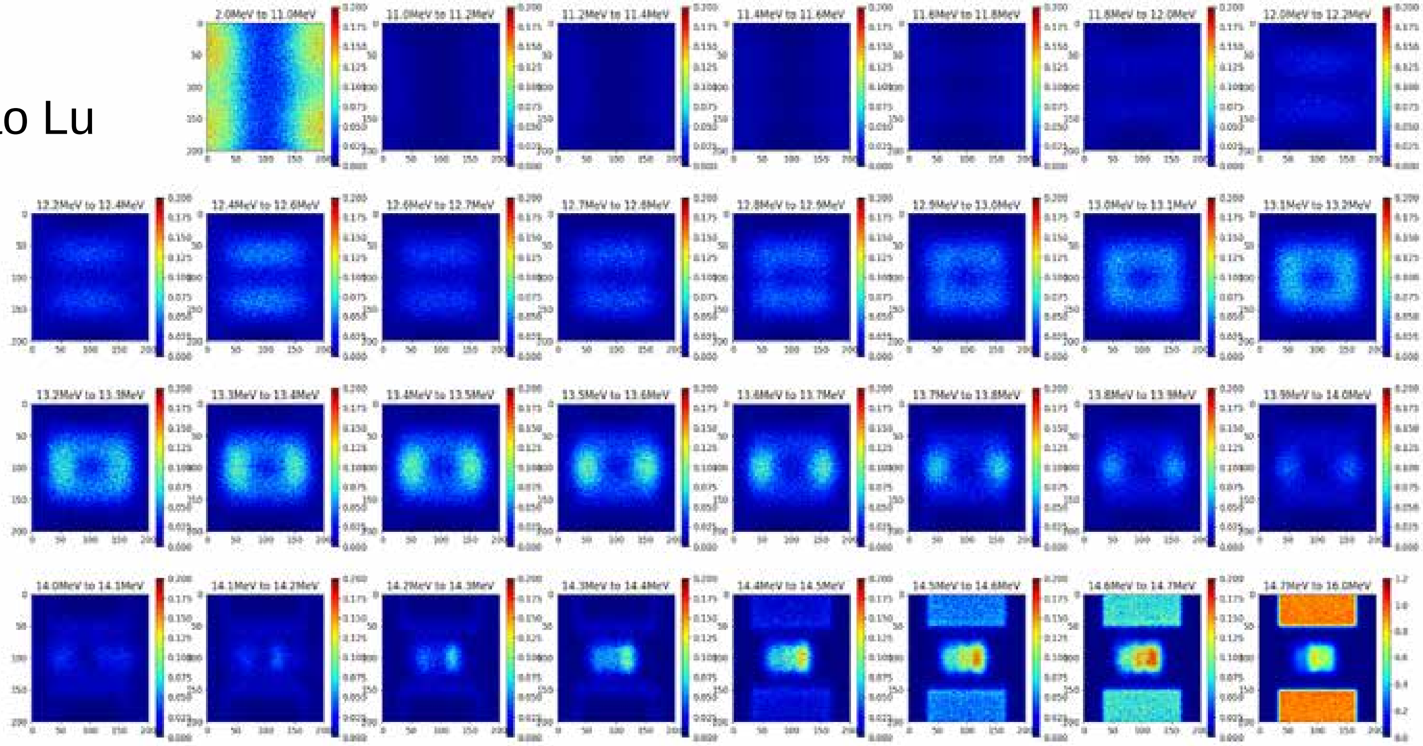
Proton view

X-ray view

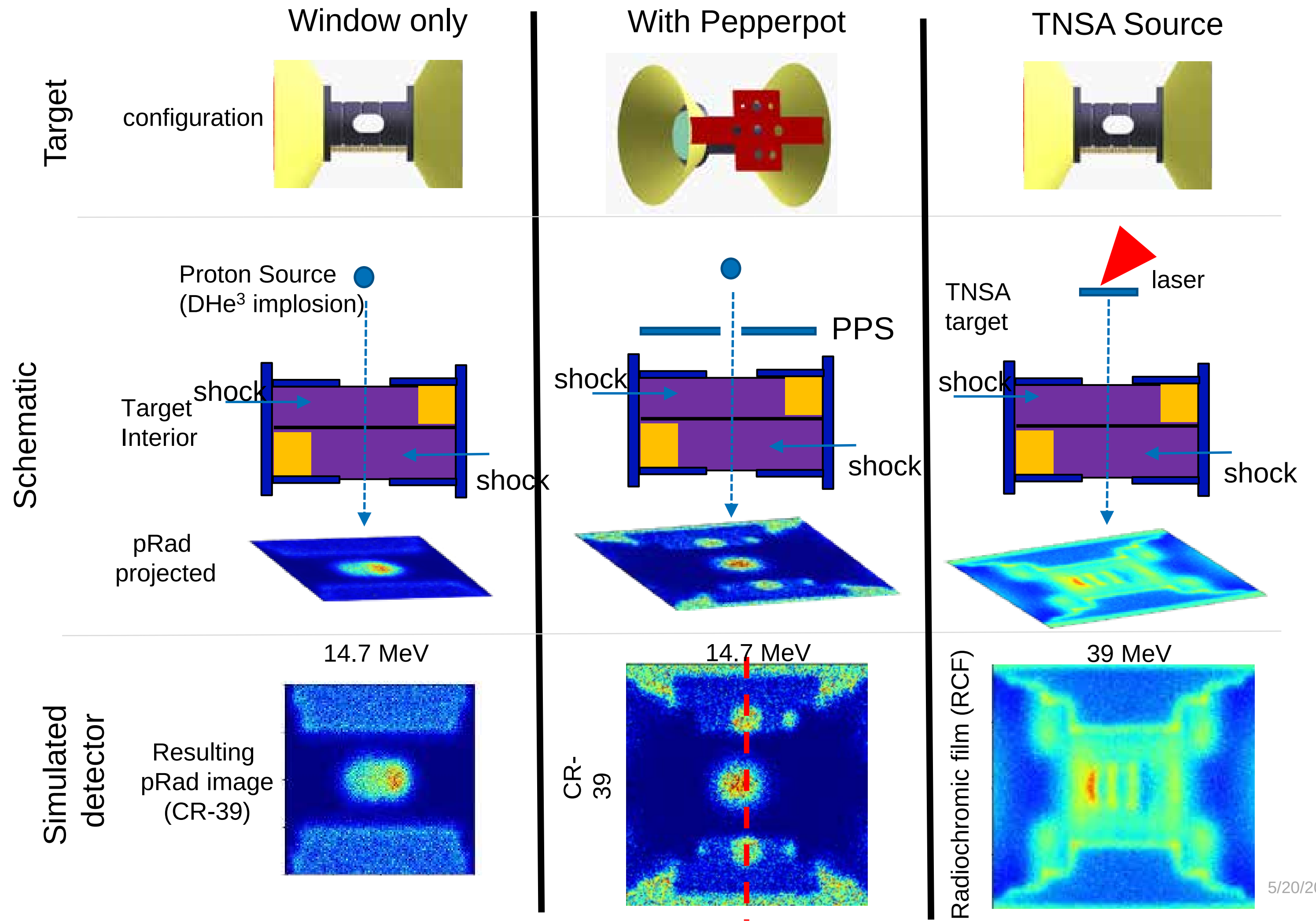
Synthetic Radiographs from Simulations for HEDB OMEGA Shots

- **MPRAD can model the images at different proton energies, which can help us optimize the etching process after the shots, each image is about 1 MeV in energy range.**

Yingchao Lu



Expected pRad



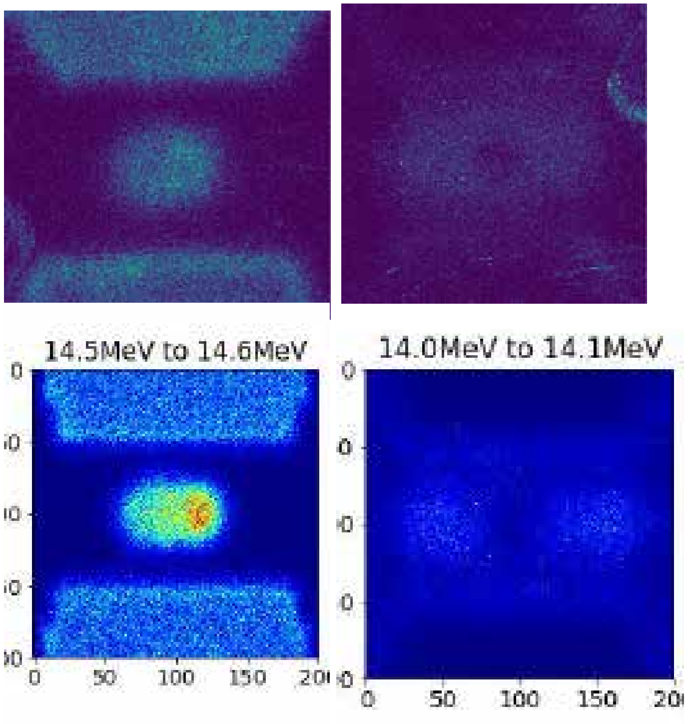
Magnetic field evolution in proton radiographs targets follows simulation predictions, but window fields are hard to disentangle

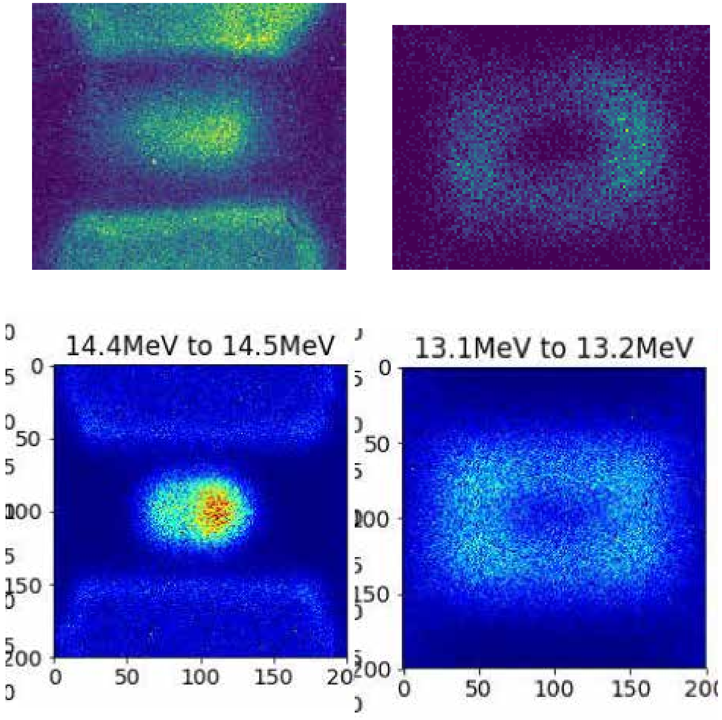
Time = 7.5 ns

Time = 8.0 ns

Experimental pRad

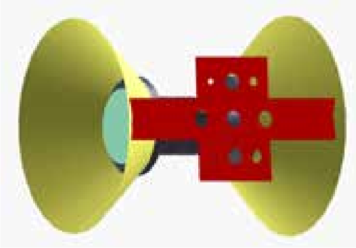
Simulated pRad





Pepper-pot foil is used to collimate proton beam and simplify proton deflection detection

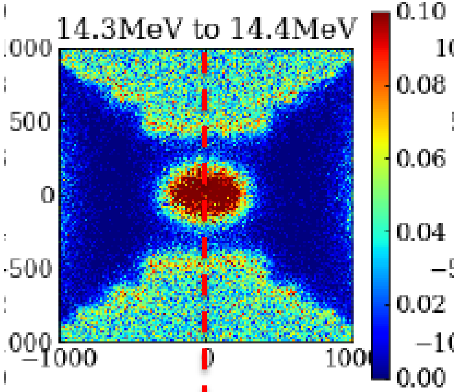
View of pepper pot foil

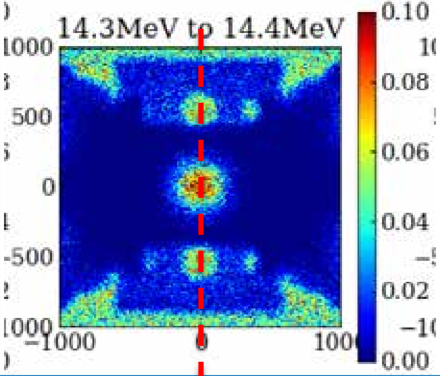


No pepper-pot

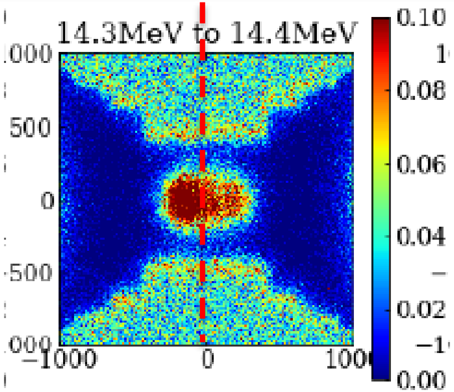
Pepper-pot

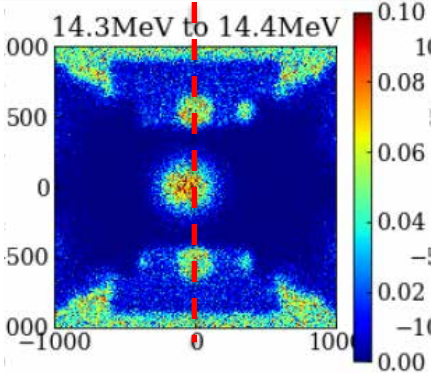
Gold target No B-field





Gold target B-field



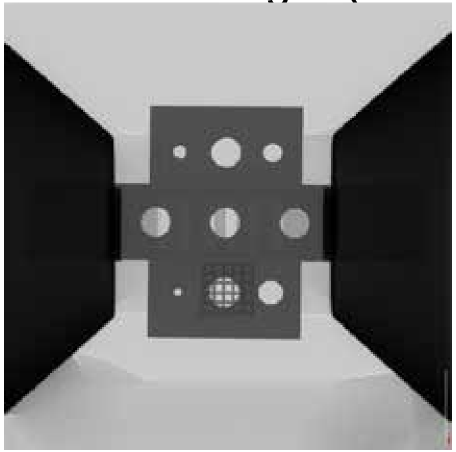


No quantifiable shift in signal without pepper pot foil

Experimental pRad images with Pepperpot, made the shift more obvious

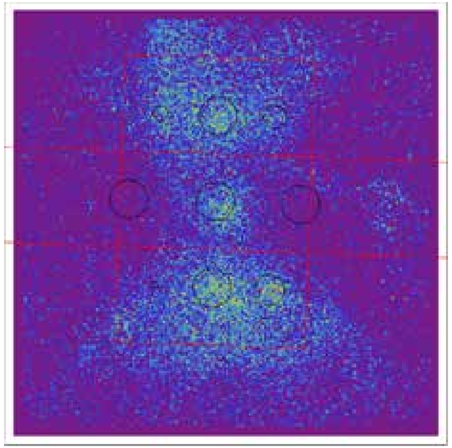
2019 PPS Results

2019 PPS Target (Versa)

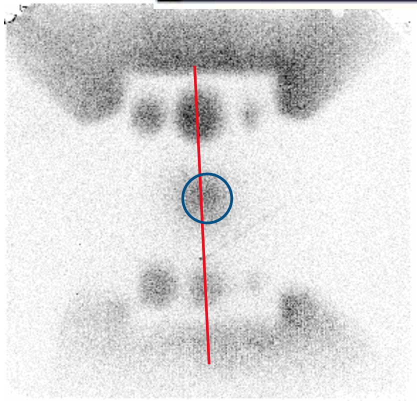


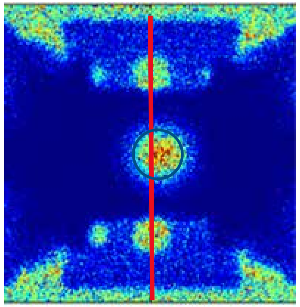
2019 X-ray IP

2019 pRad CR-39



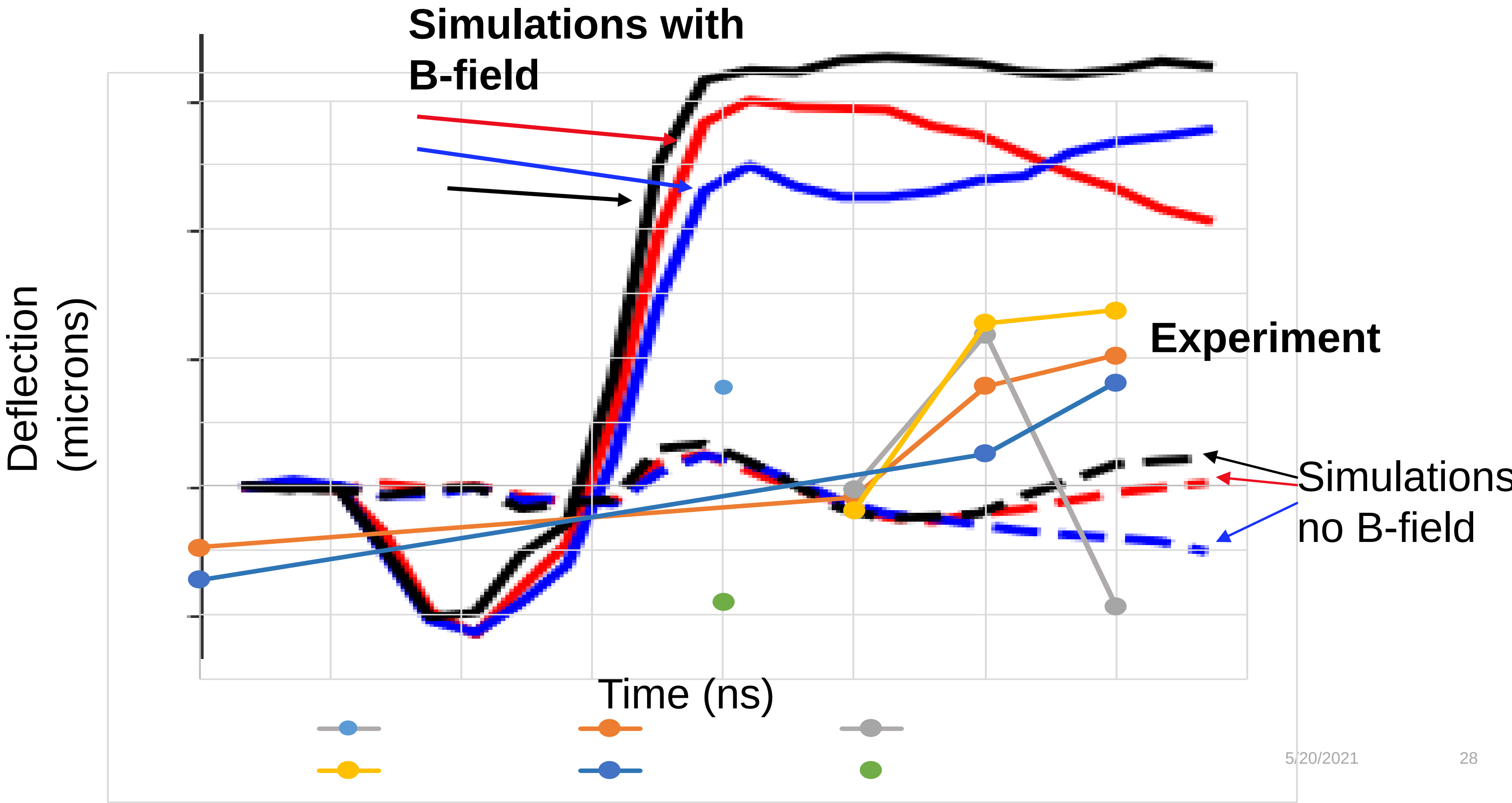
2020 Experimental pRad





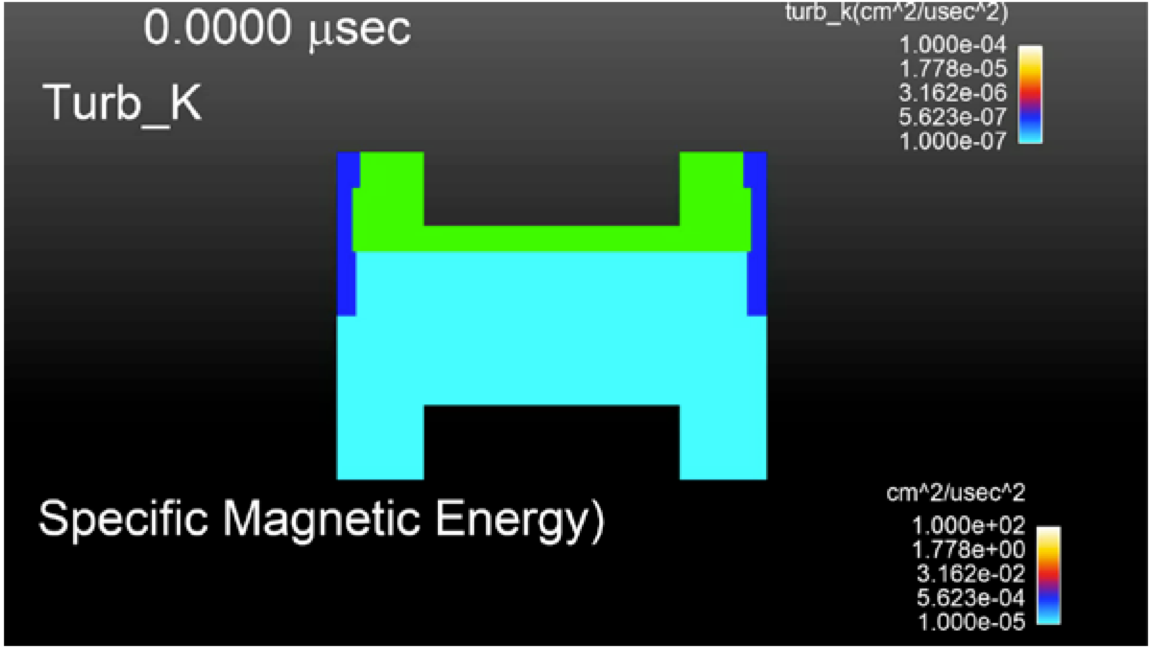
Synthetic pRad

HEDB Deflection Results show B-field of 20-30 Tesla

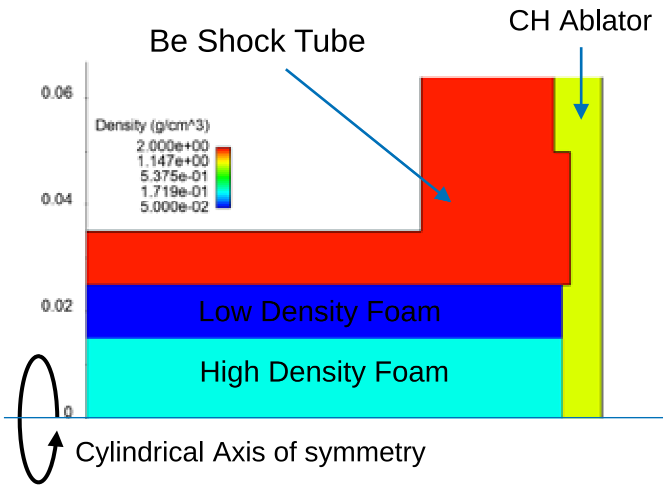


Simulation and Theory

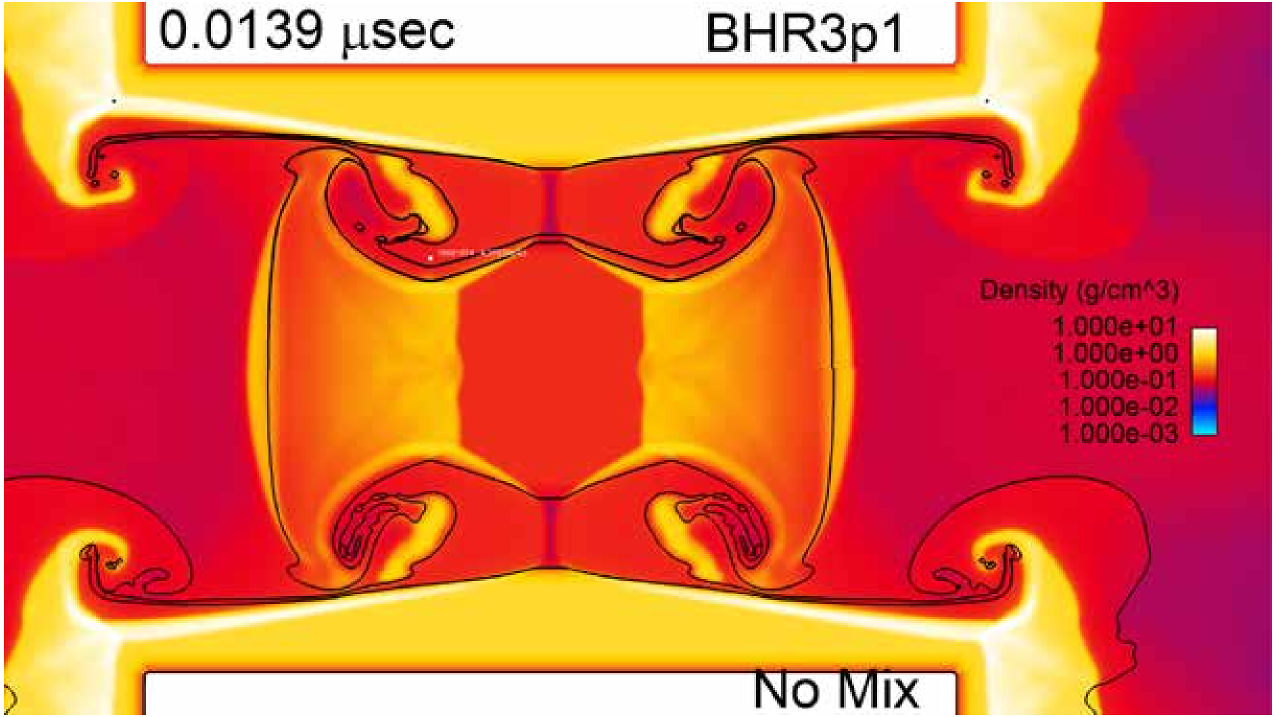
FLAG Shear Coaxial Shock-Tube Movie



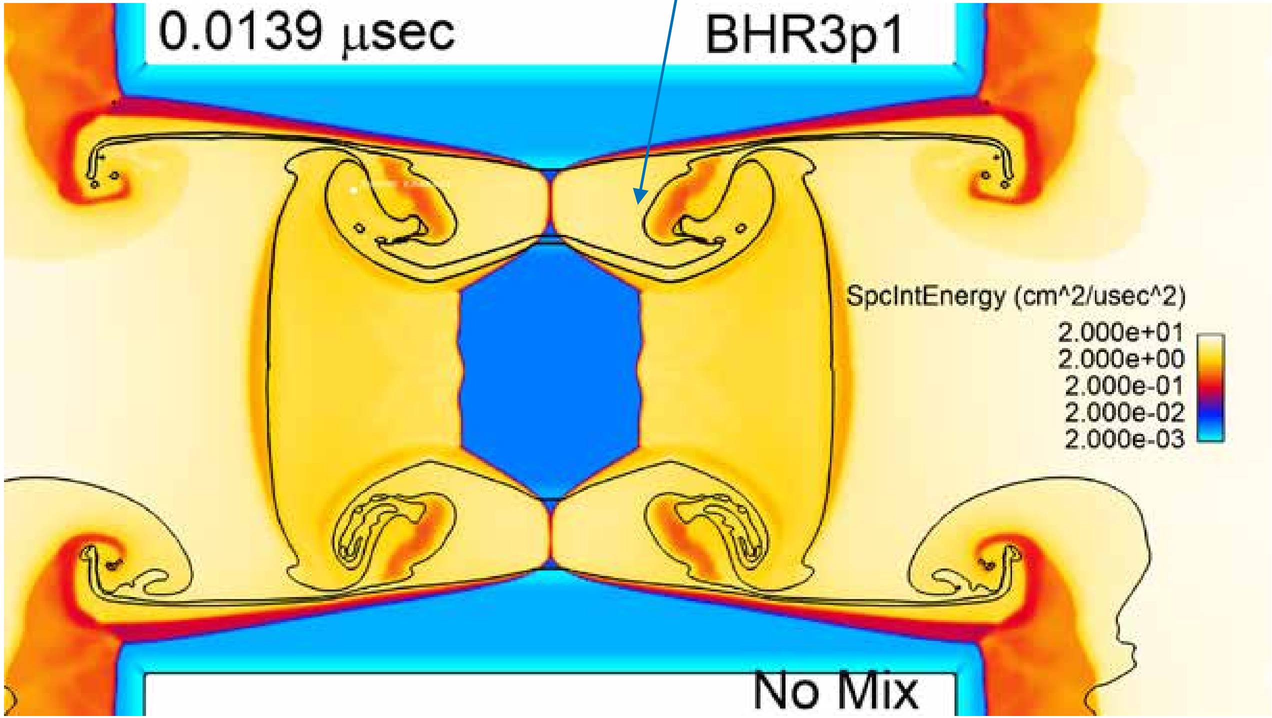
Coaxial Foam Geometry



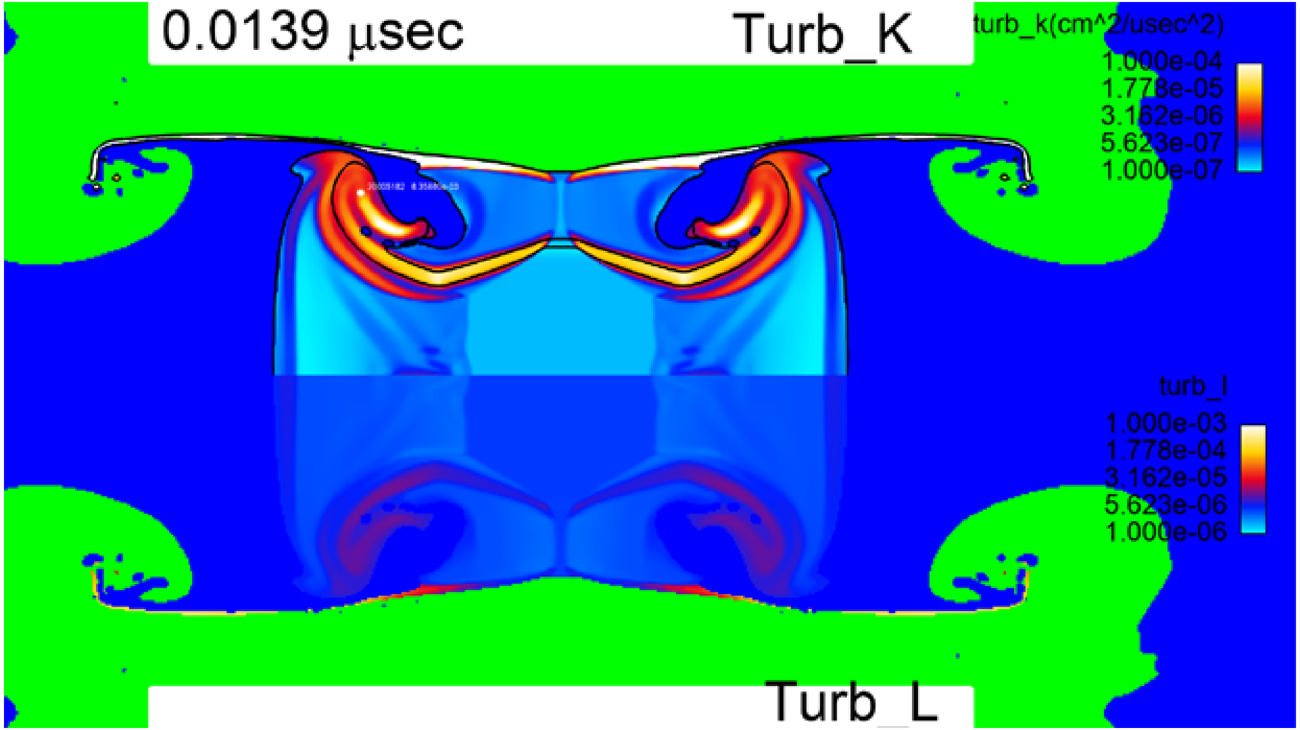
Shock convergence is insensitive to usage of the dynamic mix model.



Specific internal energy is ~8(10^{-3}) $cm^2/\ sec^2$ in the mixing layer.

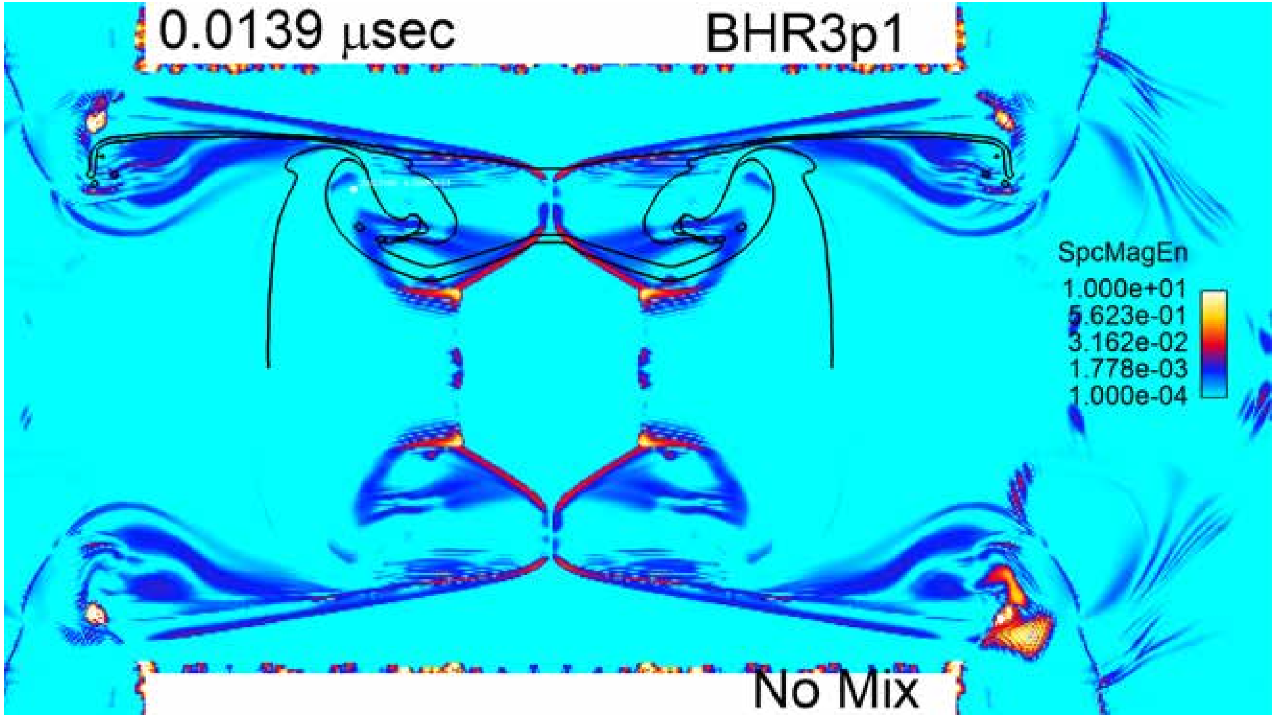


Specific Turbulent Kinetic Energy ~ $10^{-5} cm^2 / sec^2$ in the mixing layer.

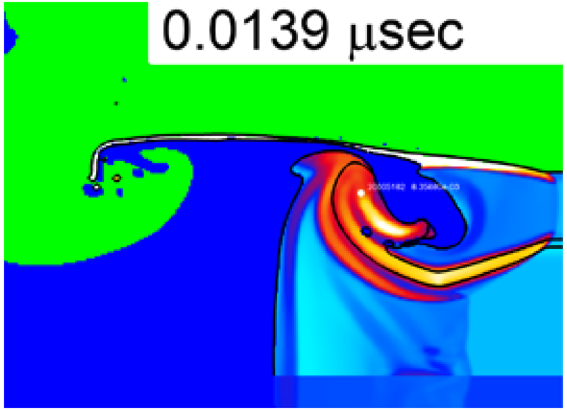


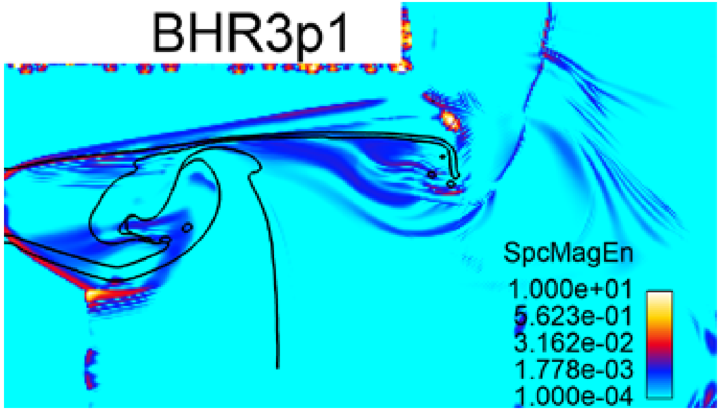
Biermann Battery generated specific magnetic energy ~ 10^{-2} $cm^2/\ sec^2$

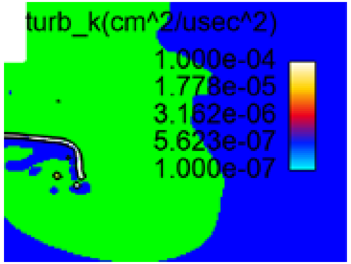
Note: This is with JXB forces zeroed out and no resistive evolution.



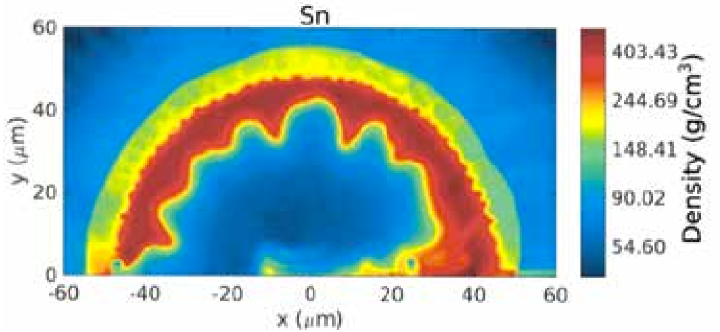
turbulence is spatially located away from the location of the magnetic field generation







Biermann Battery Process: Baroclinicity $\longrightarrow$ B Fields



$$\frac{\partial \mathbf{B_{bb}}}{\partial t} = -\frac{c}{e}\frac{\nabla n_e \times \nabla P_e}{n_e^2} \approx -\frac{c}{e}\frac{\nabla n_e \times \nabla T_e}{n_e}$$

$$\frac{\partial |\mathbf{B_{bb}}|}{\partial t} \approx 0.5\left(\frac{\mathrm{MegaGauss}}{\mathrm{ns}}\right)\left(\frac{f}{0.1}\right)\left(\frac{T_e}{5\ \mathrm{keV}}\right)\left(\frac{100\mu\mathrm{m}}{\lambda_n}\right)\left(\frac{100\mu\mathrm{m}}{\lambda_T}\right)$$

For ICF: $T_e \sim 2.5\ \mathrm{keV}, \lambda_{n,T} \sim 5\mu m$

We get: $\partial B_{BB}/\partial t \sim 10^8(\mathrm{Gauss}/ns)$

Or: $\boxed{B_{BB} \sim 10^8 \mathrm{Gauss\ in}\ ns}$ (10^4 Tesla)

(A similar magnitude of B field generation from composition gradient process. See Sadler, HL, 2020a,b)

Is this field Strong or Weak for ICF?

- Three quantities to keep in mind

ICF Hot Spot

Compare to thermal pressure

$$\beta_{\mathrm{thermal}} = \frac{nkT}{B^2/8\pi}$$

~ 100

Compare to turbulent energy density

$$\beta_{\mathrm{turb-kinetic}} = \frac{(1/2)\rho\delta v^2}{B^2/8\pi}$$

~ ??

Magnetization parameter: electron gyro-frequency over collision freq.

$$\chi_e = \Omega_{ce}\tau_e = \frac{e|\mathbf{B}|\tau}{m_e} \simeq \frac{6\times10^{16}}{\bar{Z}\ln(\Lambda)}\left(\frac{T_e}{\mathrm{eV}}\right)^{\frac{3}{2}}\left(\frac{n_e}{\mathrm{cm}^{-3}}\right)^{-1}\left(\frac{|\mathbf{B}|}{\mathrm{T}}\right),$$

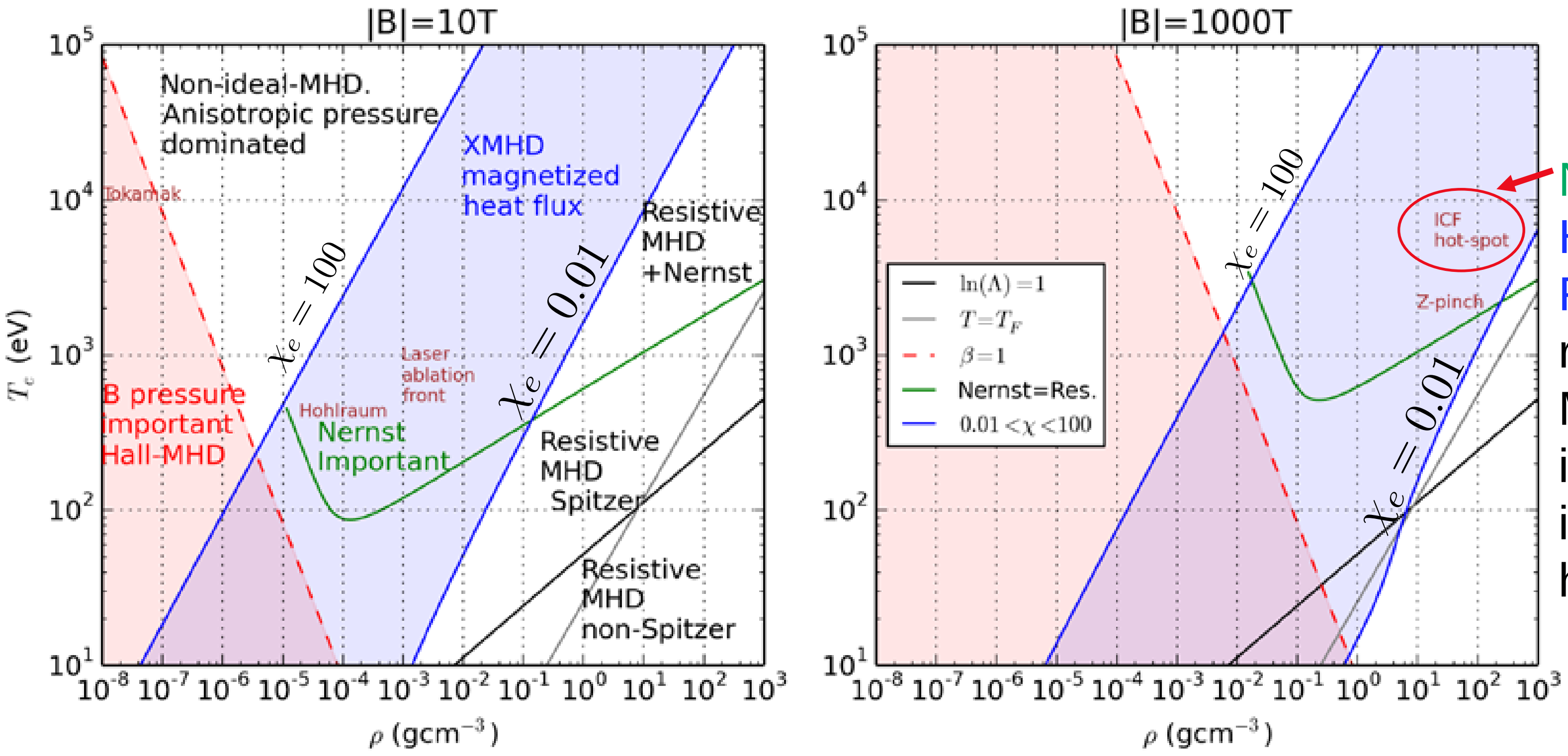
~ 1

T_e = 2.5 keV; n_e = 1e25 /cc; B = 1e8 G

Effects of Magnetic Fields with Full xMHD

Blue shaded region is where magnetized heat flux matters!

$$\mathbf{E} = -\mathbf{u}\times\mathbf{B} + \frac{\mathbf{J}\times\mathbf{B}}{n_e e} - \frac{\nabla.\underline{P}_e}{n_e e} + \frac{m_e\underline{\alpha}.\mathbf{J}}{n_e e^2\tau} - \frac{\underline{\beta}.\nabla T_e}{e},$$



Nernst, Heat Flux, and resistive MHD important in ICF hot-spot!

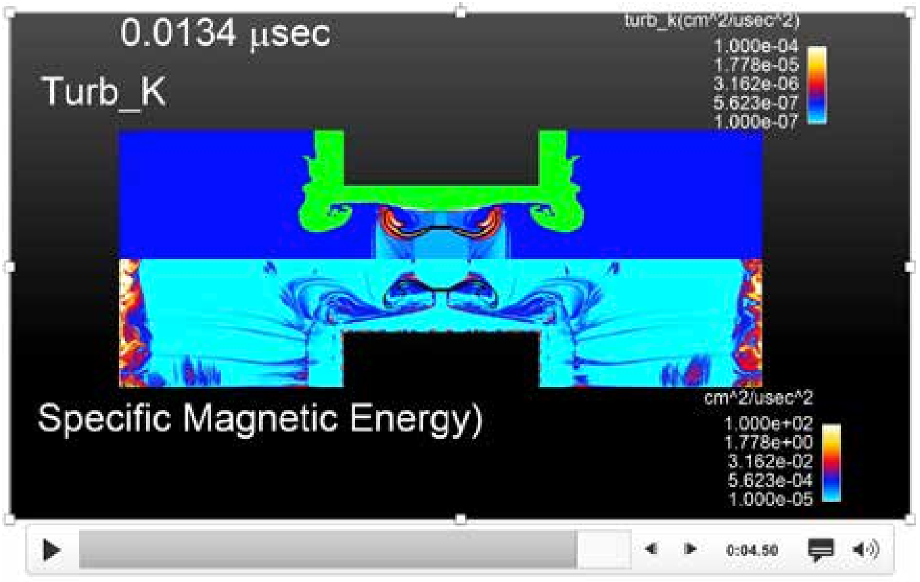
Sadler, HL, Flippo, 2021, in preparation

Implications of such magnetic fields

Implications for turbulent mix models (w. T. Gianakon, Chris Rousculp, B. Albright), ASC codes
Implications for charged particle transport
Implications for interface instabilities and experiments

Will self-generated B field affect turbulent mix?

- Implement BB term in the FLAG code. Verified with other codes such as FLASH and LA-COMPASS (led by Gianakon, Rouscoulp, S. Li)
- FLAG simulation of shock tubes with mix model shows that the self-generated BB magnetic field energy density is higher than the turbulence energy density

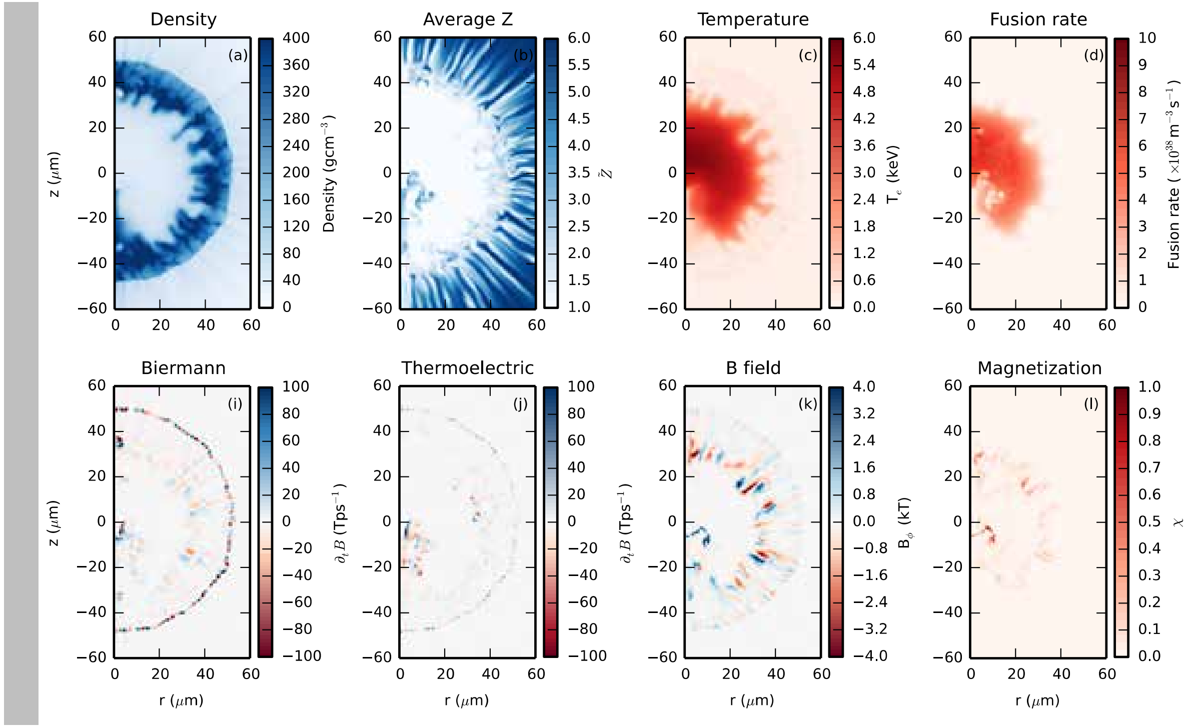


w. Turb mix model and B-field self-generation

$$\boxed{u_B > \mathrm{Turb}_K}$$

Li et al. in preparation (2021)

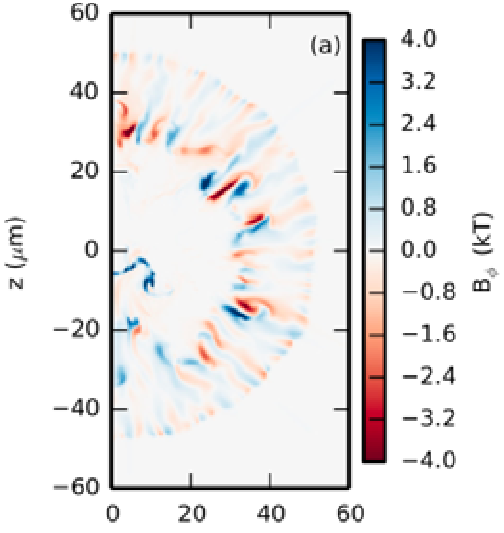
Implications for ICF: B field post-processing of xRAGE hydro simulation of an NIF shot



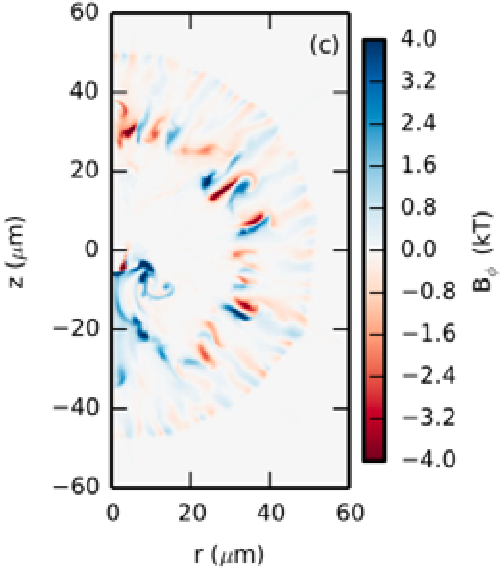
J. Sadler et al.
Phys. Plasmas 27, 072707 (2020).

The new Z gradient source term makes a difference

Biermann + Z gradient



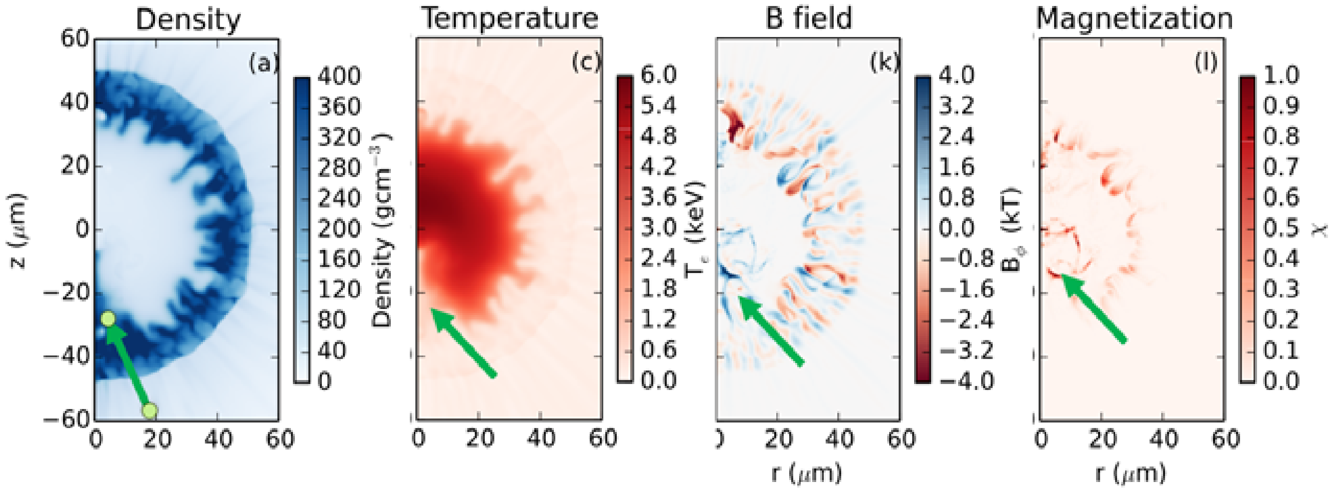
Biermann



For ICF: Electrons are magnetized by the self-generated B fields, could affect alphas as well

- Effects on electron heat conduction and charged particle transport

At both RTI and KHI interfaces

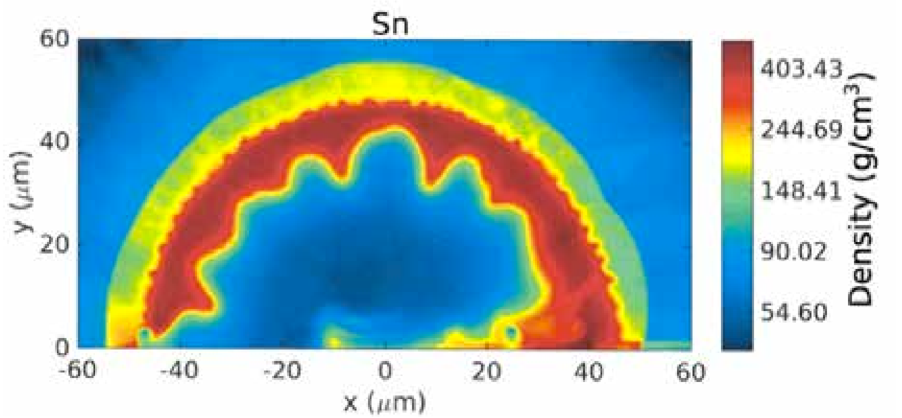


(3.5 MeV alphas)

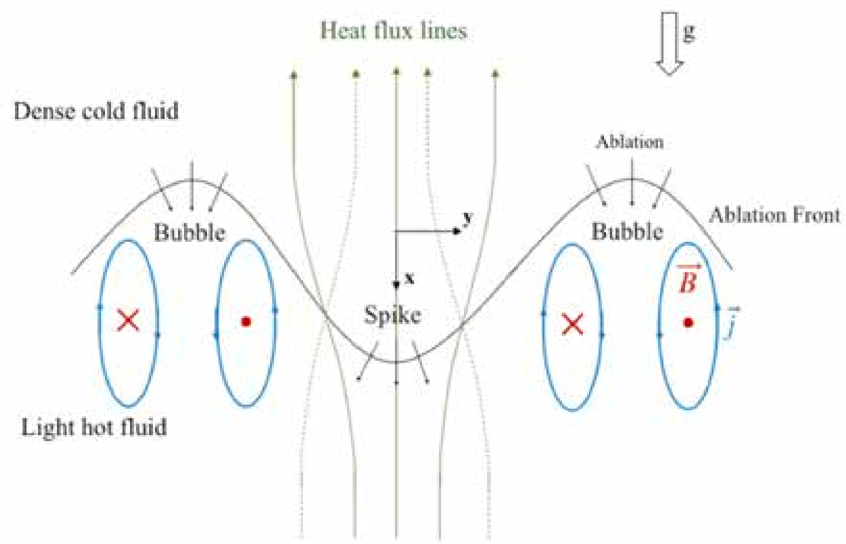
$$R_\alpha \sim \frac{100\mu m}{B/5\ kTesla}$$

Sadler, HL et al. PoP (2020)

Other Implications for ICF: altering electron heat transport and interface instabilities



mRTI with self-generated B



B-field Electron heat-flux modified KHI